CZECH POWER GRID WITHOUT ELECTRICITY FROM COAL BY 2030:

Sensitivity Analysis

2030

FINAL REPORT

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energynautics
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1. INTRODUCTION

1.1 MOTIVATION

This report presents a follow-up to the study "Czech Power Grid without Electricity from Coal by 2030", as released in May 2018.[1] It aims to address feedback and criticism issued during the press conference and stakeholder workshop at the study release in Prague. For the results presented, the simulation model used was revised and improved in a number of details. Moreover, a set of additional scenarios was analyzed to assess the sensitivity of the Czech grid under the given scenario in 2030 to a number of external factors.

1.2 GENERAL MESSAGES

Under the revised baseline scenario (analog to the scenario in the original study, but with detail improvements in the simulation model) and all sensitivity scenarios grid reinforcements in the Czech Republic are not strictly necessary for system stability, but are introduced for economic reasons.

If the Czech Republic aims to be fully self-sufficient in the future in terms of resource adequacy under the given scenarios, the installation of additional renewable energy capacities and some amount of additional gas fired generation is recommended beyond 2030 to cover cold low-VRE periods (e.g. low wind or solar energy availability). However, as it may be significantly more cost effective to meet brief periods of peak demand with imports, the benefits of pursuing a more regional approach to resource adequacy should also be further explored.

1.3 CORRECTION TO MODELLING OF HYDROPOWER

A correction was made to the modelling of hydropower assets to better reflect current operating practices and costs in the Czech market. These corrections led to a downward revision of hydro power production. When a further strengthening of interconnector capacity is assumed, hydro capacity factors also further decline due to competition with cheaper imports.

Under the new baseline scenario coal power still makes up almost 20 % of generation, while new renewables (biomass/biogas, wind and PV) provide ca. 24 % of total generation.

[1] http://bit.ly/grid-cz

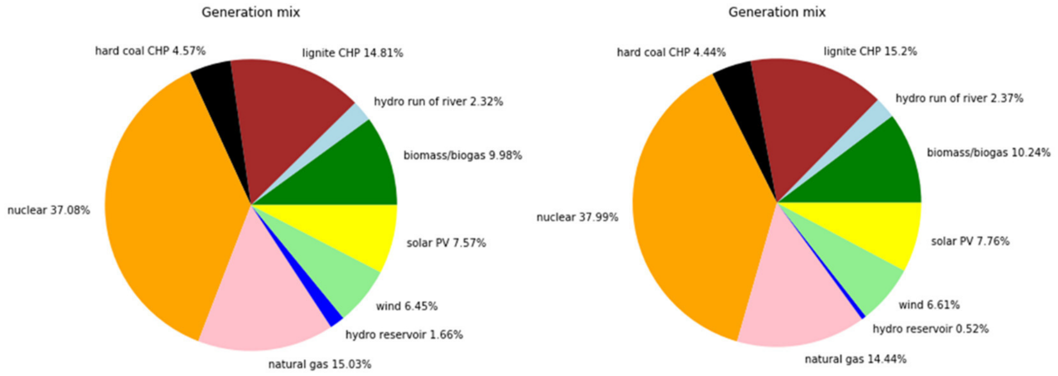

Figure 1: Generation mix by fuel source, new baseline scenario without (left) and with (right) reinforcements

The Czech Republic remains a net exporter despite these revisions, but exports are reduced, especially during the low load period in the summer. The main reason for these changing results is the fact that under the original scenario, a comparatively high share of power from hydro and gas power plants was exported during low load periods in summer, which is no longer the case with the assumed increased price of hydro.

As before, the main reinforcement that is recommended inside the Czech Republic for economic reasons is an expansion of an internal line that would allow higher in-country transfer capacities and also enable higher cross border transactions with Slovakia and Poland.

In terms of security of supply, the load can be covered domestically even without PV with Dukovany fully operational. With only three blocks operating, on the other hand, the system operates very close to its capacity maximum, without PV. In both cases, all CHP units (gas, coal and biomass/biogas) are constantly running at full output, only in some cases slightly decreasing output during the night.

While there is no critical shortage in either case, the system is rather dangerously close to its firm capacity limit. Non-availability of hydro (water freezing) or coal units, which may experience issues with fuel supply during very cold periods, would lead to a shortage. It can be covered through imports, however, it would be advisable to consider maintaining roughly 1 GW of cold reserve plants as a backup for such periods. Cold reserve plants are typically older units that are mothballed and can be reactivated with a couple of days or weeks of lead time. For example, cold reserves in Austria and Germany consisting mainly of unprofitable older gas or oil fired units have been activated in Austria and Germany in some winters in the past decade. Moreover, Germany has just moved several lignite fired blocks to cold reserve. While it is generally infeasible to decommission an entire lignite power plant and keep it as cold reserve due to the mining and transport infrastructure that has to be maintained along with it, it is possible to mothball and preserve older blocks of a power plant where other blocks continue operation. Under the proposed scenario, 525 MW of lignite fired generation is phased out in plants that continue operation

(Mělník, Tisová, Opatovice), these can thus be used as cold reserve. Moreover, the hard coal fired power plant at Dětmarovice (800 MW) could me retained as well.

1.4 SCENARIO A: DUKOVANY DECOMMISSIONED

Scenario A assumes a decommissioning of the Dukovany nuclear power plant, and then simulates three scenarios in which:

- This capacity is replaced by new biomass and gas capacity,
- The capacity is replaced and grids are optimally reinforced,
- The capacity is not replaced.

The scenario in which Dukovany is shut down without being replaced shows that all things being equal it would result in Czech Republic no longer being able to cover peak demand domestically at all times. This however continues to be guaranteed in the scenarios where the capacity is replaced. In other words, additional dispatchable capacity is needed if this standard of security of supply is desired.

Under all but one of these scenarios (Dukovany is replaced, but no optimal grid reinforcements) the Czech Republic becomes a net importer. This is largely due to the fact that it often becomes cheaper to import power than to use the domestic gas fired units, which also operate at a lower level of economic viability.

Compared to the baseline scenarios there are slight changes to economically optimal grid reinforcement. In particular, interconnection capacity to Poland is slightly reduced due to lower Czech exports, while interconnection capacity to Slovakia is slightly increased due to rising imports. This reinforcement would leave the Czech grid in a similar situation as the Swiss grid, which is a main hub for flows between France, Italy and Germany. These investments would allow the Czech Republic to benefit from a reduction in the overall cost of electricity in the country. However, it also highlights the need for an integrated European approach to grid planning, reinforcement and cost-sharing in the meshed grid of the European internal electricity market.

1.5 SCENARIO B: REDUCED IMPORT

Scenario B retains the same capacities and operational procedures for the Czech system as the baseline scenario, but assumes a "less optimistic" development in regards to firm generation capacity in Poland, Germany and France. Under this scenario, Poland retires some of its coal fleet, Germany implements a partial coal exit, and France retires 20 GW of its nuclear fleet. In parallel each country also adds variable wind and solar capacity.

While the developments in Germany and France draw German export capacities to the West and reduce export capacities to the Czech Republic, developments in Poland increase Poland's reliance on imports during peak hours with low wind. This leaves the

Czech Republic in the situation that it can a) not always rely on imports and b) needs to support the Polish system.

These developments also result in the highest net exports from the Czech Republic across all scenarios in particular when no grid reinforcement is assumed. This is due in part to higher exports compared to Scenario A and C, and in particular to lower imports / transit flows from Slovakia (see below). Capacity factors for hard coal, CCGT and OCGT plants also increase considerably.

Interestingly, despite increased Czech exports and the increase of wind and solar capacity in the surrounding countries the scenario leads to less grid expansion in the Czech Republic compared to the baseline scenario. This is largely due to the fact that the decommissioning of a number of coal units in Poland makes a direct reinforcement of lines between Slovakia and Poland a better solution than to reinforce the Czech grid for transit flows from Slovakia to Poland. These reduced transit flows reduce strain on the Czech grid, while leaving existing line capacities sufficient for direct exports from the Czech Republic to Poland. These results highlight again the need for integrated European capacity and grid planning.

As an additional study case, the Czech capacities from Scenario A (Dukovany decommissioned), were combined with the capacities in neighboring countries in Scenario B. The results show that even without Dukovany the Czech system can remain a clear net exporter and export during almost all periods if the market conditions in the neighboring countries call for it. Moreover, the analysis shows that the system would be able to cover its load even in winter if coordinated action from pumped storage plants taken. While more backup capacity may be desirable to not become dependent on peak imports during cold weather events, the capacities for such imports are also available in Austria, which operates large overcapacities of fast reacting hydro power plants. This demonstrates that neither new nuclear power plants in the Czech Republic and nor new cold reserves are clearly necessary for security of supply.

1.6 SCENARIO C: STORAGE, HEAT PUMPS AND EV

Scenario C depicts a scenario in which the Czech electricity grid is faced with increased load from heat pumps and EVs adding an additional source of flexibility and stress on the grid. The scenario also assumes a 50% deployment of battery storage with rooftop solar installations.

It is notable that due to the increased loads gas and hydro power plants show significantly higher capacity factors than in the baseline scenario when the grid is significantly reinforced. However, the relative share of renewables in the generation mix also decreases as no new capacity is assumed to be built compared to the baseline scenario. Moreover, the capacity factors of the coal CHP plants are also projected to increase slightly.

Due to increased loads, exports are lower and imports are higher than in the baseline scenario. This is in part due to the Czech Republic drawing on cheaper peak capacity in neighbouring countries where economically beneficial. The Czech Republic is still a net exporter in the scenario in which grids are not optimally reinforced as import capacity is not developed as much. The economically optimal grid reinforcement is also reduced in general, as the role of the Czech Republic facilitating transit flows reduces with more of the imports being consumed domestically. Nonetheless, the Czech Republic becomes a net importer for economic reasons if grid bottlenecks are removed due to better access to cheaper peaking capacities abroad. Average power prices in this scenario are similar to those in the baseline scenario, while higher load peaks incur higher peak prices.

From an electricity balancing perspective, the impact of storage is rather low, mainly shifting PV power to the evening uptake in demand leading to lower exports during the day and lower imports during the evening. The overall balance is largely unaffected. The impact on the distribution grid, where most PV units are connected, may however be significant.

From a security of supply perspective, the increased load from EVs and heat pumps leads to the Czech Republic not being able to cover peak demand in the modelled low temperature winter week in January, drawing instead on imports. This rise in demand could therefore give the Czech Republic a similar winter profile to France, which is a great exporter of electricity, but still becomes partially dependent on German imports during winter peak hours. This rise in demand would therefore require careful coordination between the Czech Republic and its neighbours to ensure sufficient regional capacity is available in case of reliance on imports, and either a cold reserve or other additional capacity if the Czech Republic is to remain completely self-sufficient.

2. BASELINE SCENARIO

2.1 MODEL REVISIONS

2.1.1 Hydro Model

One of the main points of criticism issued by the expert panel at the release of the original study was that the contribution of hydro reservoirs to the Czech system was likely overestimated. This point of criticism has been evaluated and found to be partially true. The original hydro model was based on historical price data from the previous decade as well as storage constraints. The prices with which hydro operators bid into the market is not strictly based on the variable cost of generation, which is very low, but on cost of opportunity. Operators will try to optimize their income and hence adjust prices depending on the average marginal price in the market. As marginal prices in the Czech system have historically been low compared to the neighboring countries, Czech hydro operators tended to bid at low costs as well, averaging between 20 and 40 € per MWh.

With the shift towards a combination of renewables and natural gas fired generation, marginal prices in the Czech system rise (the marginal unit will in most cases now be a gas power plant instead of a coal unit). Using the historical prices results in rather high capacity factors for Czech reservoir hydro. While the results from the original study would not per se deplete the reservoir levels completely, the secondary role of Czech hydro power plants as quick starting reserve and backup for unplanned outages of large (especially nuclear) conventional generating units may be endangered. To account for this, hydro prices were modified to not drop below 65 € per MWh with full reservoirs, and prices rising with lowering reservoir levels. The results are annual capacity factors that without any grid constraints are in the range of 20-30 %, in some cases up to 35 %, which is largely in line with today's potential. Hydro reservoirs provide power during the peak hours and stand by as reserves during off-peak hours. The resulting decrease in hydro production is clearly visible in the lower overall generation in the Czech Republic under the examined scenario. Czech Republic, however, remains a net electricity exporter. Grid expansion, reinforcing mainly lines that connect the Czech system to its neighbors, result in lower hydro capacity factors, as cheaper peaking power can be imported from Austria and Germany.

The revised model will be used as a baseline for all further scenarios described in this annex. In the following, the results from the baseline scenario are described in more detail than in the original report. The report chapters on power system impact of the original report remain valid, as the difference between the scenarios is simply an up to 50 % lower hydro production, with production now focused on peaking hours. Reservoir hydro provide only 1-2 % of annual production in the Czech Republic, so the difference overall is below 1 %. The key high-VRE generation situations did not change with the revision of the hydro model. More detailed information on the generation mix for the weeks picked as dispatch examples is included upon request. Additionally, a month with extremely low temperatures (-15°C and below) has been modelled and added as an additional study case.

The pumped storage model used in the original study yielded realistic results and is thus retained. The model analyzes the expected net demand (demand that is not covered by wind and solar) before the actual yearly optimization and calculates the operating times of pumped storage plants based on the expected electricity prices and the spread between pumping and turbining prices necessary for economic operation. Additionally, pumped storage plants always retain a certain state of charge to be available for backup and/or reserve duties. Pumped storage plants are not considered to be a type of renewable energy, but a means of energy storage in the evaluation of results.

2.1.2 Additional Information

The additional information described in the following subsections was added upon request.

2.1.2.1 Clarification: Increase in Hydro Capacity

The slight increase in hydro power capacity in the Czech system under both the original and the updated scenarios stems from additional small hydro power plants (< 10 MW). The currently installed large plants remain unchanged.

2.1.2.2 Correction: Weather data.

The weather data used in both the original report and in this annex is from 2011, while the original report erroneously states 2012. The data set used is available at the US Department of Commerce's Earth System Research Laboratory[2] and is based on worldwide weather reanalysis data provided by NASA. Wind and solar time series were generated according to the methodology set out by TradeWind in 2008. The data set is the same that was used in the Greenpeace powE[R] 2030 study.[3]

2.1.2.3 Clarification: Grid Reinforcements

As this issue may have not been sufficiently clear in the original report: The optimizer allows for expansions in the entire European system. Import and export balances for the Czech Republic may thus also change with grid reinforcements due to the elimination of grid congestion in neighboring countries and easier access to cheaper resources. In this regard, the simulations with reinforced grids basically present a case where all major trade

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[2] https://www.esrl.noaa.gov/psd/repository

[3] https://www.greenpeace.de/files/publications/201402-power-grid-report.pdf

barriers for electricity have been removed (almost the ideal market case) while the non-reinforced cases present the more realistic case with grid bottlenecks.

Within this study, only the extra high voltage level (220 kV and above) was modelled in detail. The impact of the proposed scenarios on the distribution grid could not be evaluated. It should be noted that a shift towards a more decentralized generation structure may require upgrades in some areas of the distribution grid as well, especially in areas with high installed wind and solar capacities.

A few distribution interconnectors, especially at 110 kV level, cross borders into neighboring countries and thus theoretically contribute to cross border trade. However, 110 kV grids are almost always run as fully radial grids, so a 110 kV line from the Czech Republic to a neighboring country will almost always simply supply a limited area across the border with power, without any significant impact on the transmission grid.

2.1.2.4 Cross border transactions by country

Annual cross border volumes (flows) by country for all scenarios are included in an appendix. While the tables in sections 2.2.1, 3.2.1,4.2.1 and 5.2.1 consider the overall country balance the individual country specific values seem to be higher, but add up to the same balances. The reason is that while CZ is considered to be exporting overall (generation surplus), it may still be importing from one or two other countries, passing on more power on the other borders at the same time.

2.1.2.5 Extreme conditions

Extreme weather conditions and their impact on generation were largely neglected in the simulations of the original report. All cases were calculated with an average weather year (average insolation, wind and rain, no significant extreme weather events such as heavy storms, drought periods etc.). As an indicator, a study case of the original scenario with extremely cold weather is presented in 2.2.4 of this annex.

Generally, in situations of extreme cold (which is considered to be the most critical case), the problem lies with conventional stations – rivers freeze and ice can jam the cooling water intakes or turbine inlets of hydro power plants (which is a rare occurrence in central Europe, but could happen within this once-in-a-hundred-years extreme scenario with average temperatures below -10° C for weeks). Stations firing brown coal with a high water content can experience problems with freezing fuel bunkers, although this problem has generally been taken care of by heating and a higher degree of mechanization in the Czech Republic. PV on the other hand are almost immune to low temperatures, but lose efficiency at high temperatures (which is considered in the PV time series used). Snow coverage of PV panels can reduce the already low output in winter, which is considered in the simulations. Wind turbines may experience icing problems in winter, however, in European conditions, temperatures rarely drop low enough for that to happen.

2.1.2.6 Load distribution

For all simulations, a fixed load distribution key was used – load distribution is the same in every time step, only the load's magnitude changes. The load profile was developed based on NUTS region population data, with the simplification that load is roughly distributed the same. The path and results are shown in Table 1. Each NUTS region is assigned to one or more nodes (in the latter case, equal distribution is assumed), from which the population and this load share of each node is calculated.

Table 1: Annual capacity factors by technology.

Code	Region	Inhabitants	CZ01	CZ02	CZ03	CZ04	CZ05	CZ06	CZ07	CZ08	CZ09	CZ10	CZ11	CZ12	CZ13	CZ14
CZ010	Praha	1,280,508	0	0	0	0	0	0	0.5	0	0.5	0	0	0	0	0
CZ020	Středočeský kraj	1,338,982	0	0	0	0	0	0	0.333333	0	0.333333	0	0	0.333333	0	0
CZ031	Jihočeský kraj	638,782	0	0	0	0	0	0	0	0	0	0	0	0	0	1
CZ032	Plzeňský kraj	578,629	0	0	0	0	0	0	0	0	0	0	1	0	0	0
CZ041	Karlovarský kraj	296,749	0.5	0	0	0	0	0	0	0	0	0	0.5	0	0	0
CZ042	Ústecký kraj	821,377	0.5	0	0	0	0.5	0	0	0	0	0	0	0	0	0
CZ051	Liberecký kraj	440,636	0	0	0	0	0	1	0	0	0	0	0	0	0	0
CZ052	Královéhradecký kraj	550,804	0	0	0	0	0	0.5	0	0.5	0	0	0	0	0	0
CZ053	Pardubický kraj	517,087	0	0	0	0	0	0	0	1	0	0	0	0	0	0
CZ063	Kraj Vysočina	508,952	0	0	0.5	0	0	0	0	0	0	0	0	0	0.5	0
CZ064	Jihomoravský kraj	1,178,812	0	0	0.333333	0.333333	0	0	0	0	0	0	0	0	0.333333	0
CZ071	Olomoucký kraj	633,952	0	0	0	0	0	0	0	0.5	0	0.5	0	0	0	0
CZ072	Zlínský kraj	583,698	0	0	0	0.5	0	0	0	0	0	0.5	0	0	0	0
CZ080	Moravskoslezský kraj	1,209,879	0	1	0	0	0	0	0	0	0	0	0	0	0	0
		Inhabitants per node	559,063	1,209,879	647,413	684,786	410,689	716,038	1,086,581	1,109,465	1,086,581	608,825	727,004	446,327	647,413	638,782
		Demand share	5.28%	11.44%	6.12%	6.47%	3.88%	6.77%	10.27%	10.49%	10.27%	5.76%	6.87%	4.22%	6.12%	6.04%

2.2 RESULTS

2.2.1 Energy Balances

The import/export characteristics of the original scenario (with higher hydro potential) and the new baseline scenario with the revised hydro model are given in Table 2. The Czech Republic remains a net exporter of electricity on both cases, but the exports are reduced. The main reason for this is the fact that under the original scenario, a comparatively high share of power from hydro and gas power plants was exported during low load periods in summer, which is no longer the case with the increased price of hydro.

Table 2: Import/export balances.

	Original scenario		**Baseline scenario with updated hydro model**	
	No reinforcements	Optimized reinforcements	No reinforcements	Optimized reinforcements
Demand	65 TWh	65 TWh	65 TWh	65 TWh
Losses[4]	4 TWh	4 TWh	4 TWh	4 TWh
Net generation	76.45 TWh	73.20 TWh	72.99 TWh	70.52 TWh
Imports	0.65 TWh	1.53 TWh	1.42 TWh	2.54 TWh
Exports	8.10 TWh	5.73 TWh	5.40 TWh	4.06 TWh
Balance	7.45 TWh	4.20 TWh	3.99 TWh	1.52 TWh

The resulting annual generation mix for both cases (not grid reinforcements, and fully optimized grid) are given in Figure 2. Coal power still makes up slightly less than 20 % of generation, while new renewables (biomass/biogas, wind and PV) provide ca. 24 % of total generation.

[4] Estimated based on CEPS experience.

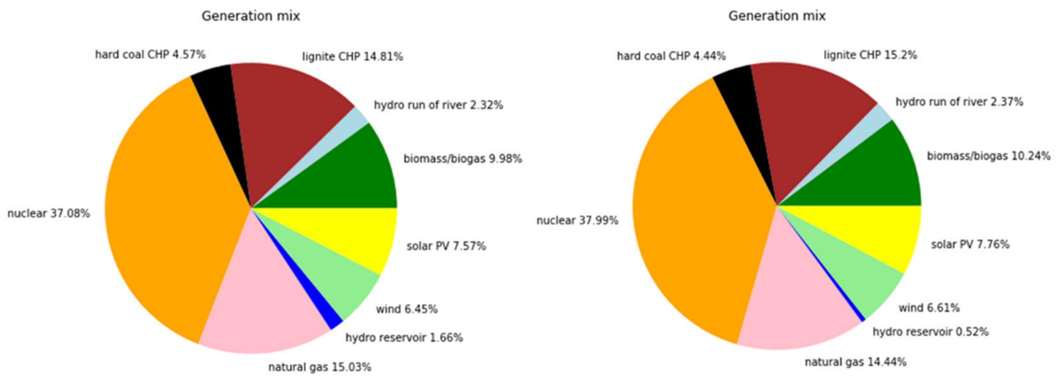

Figure 2: Generation mix by fuel source, new baseline scenario without (left) and with (right) reinforcements. (Source: Simulation results.)

Capacity factors by technology are given in Table 3. It is clearly visible that the capacity factors of peaking plants (hydro and OCGT) are greatly reduced by the grid reinforcements, which allow for cheaper imports during peaking hours. Nuclear, CHP and biomass plants run at almost the same capacity factors, while the impact on CCGT plants is existent, but low.

Table 3: Annual capacity factors by technology.

Technology	Annual capacity factor without reinforcements	Annual capacity factor w/ optimized reinforcements
Biomass and biogas	60.07%	60.05%
Natural gas CCGT	37.90%	31.49%
Natural gas small CHP	92.86%	91.97%
Natural gas OCGT	21.09%	0.00%
Hard coal CHP	72.24%	64.59%
Hydro PS generation	6.28%	0.78%
Hydro PS pumping	6.50%	1.07%
Hydro reservoirs	34.50%	2.28%
Hydro run of river	53.13%	53.08%
Lignite CHP	72.65%	71.99%
Nuclear Dukovany	74.99%	74.99%
Nuclear Temelín	79.46%	79.47%
PV	11.47%	11.47%
Waste incineration	99.97%	99.94%
Wind	26.22%	26.22%

2.2.2 Reinforcements

Under the revised baseline scenario, grid reinforcements in the Czech Republic are not strictly necessary for system stability, but are mostly introduced for economic reasons – they allow for more transactions with neighboring countries. Grid reinforcements are recommended in the eastern part of the country, as indicated in section 3.2.2 of the original report. As before, the main reinforcement that is recommended inside the Czech Republic is an expansion of the Sokolnice-Prosenice corridor, which currently consists of a double 220 kV line and a single 400 kV line. Upgrading it to overall four 400 kV circuits will allow for higher in-country transfer capacities and also enable higher cross border transactions with Slovakia and Poland.

This is clearly reflected in the results (Table 7), which recommend some more reinforcements mainly on cross border lines. A large part of grid reinforcements is driven by the Polish dependency on imports, reinforcing the corridor between Slovakia and Poland. The Czech Republic is a major exporter to Poland, while importing (often at the same time) to a lesser degree from Slovakia.

Table 4: Grid reinforcements in CZ, Scenario A.

Line	Action	Impact
400 kV line Sokolnice-Prosenice	Additional 400 kV circuit	Corridor Slovakia-CZ-Poland
220 kV line Sokolnice-Prosenice	Upgrade of double circuit line to 400 kV	Corridor Slovakia-CZ-Poland
Border CZ-PL (Nosovice-PSE)	New 400 kV circuits on the lines from Nosovice to the PSE grid (Dobrezen, Wielopole, Kopanina or Bujaków)	Corridor Slovakia-CZ-Poland
400 kV Nosovice-Varin (SK)	Two additional 400 kV circuits	Corridor Slovakia-CZ-Poland
400 kV line Sokolnice-Stupava (SK)	Two additional 400 kV circuits	Corridor Slovakia-CZ-Poland

With the revised hydro model, the connection to Austria is still often highly loaded, but needs no reinforcement.

2.2.3 Dispatch Examples

The dispatch examples for weeks in January, July and October, as in the original report, remain very similar – the share of reservoir hydro is lower, while the pumped storage plants see slightly more action, but the general aspects are the same as described in section 3.1.2 of the report. Graphics are included here for comparison to the other scenarios

– a week in June is also added to provide an example of a week with high PV and high exports (Figure 3 to Figure 6). Additionally, the generation shares by fuel source for all example weeks are given in Figure 7. All cases are taken from the simulation without grid reinforcements.

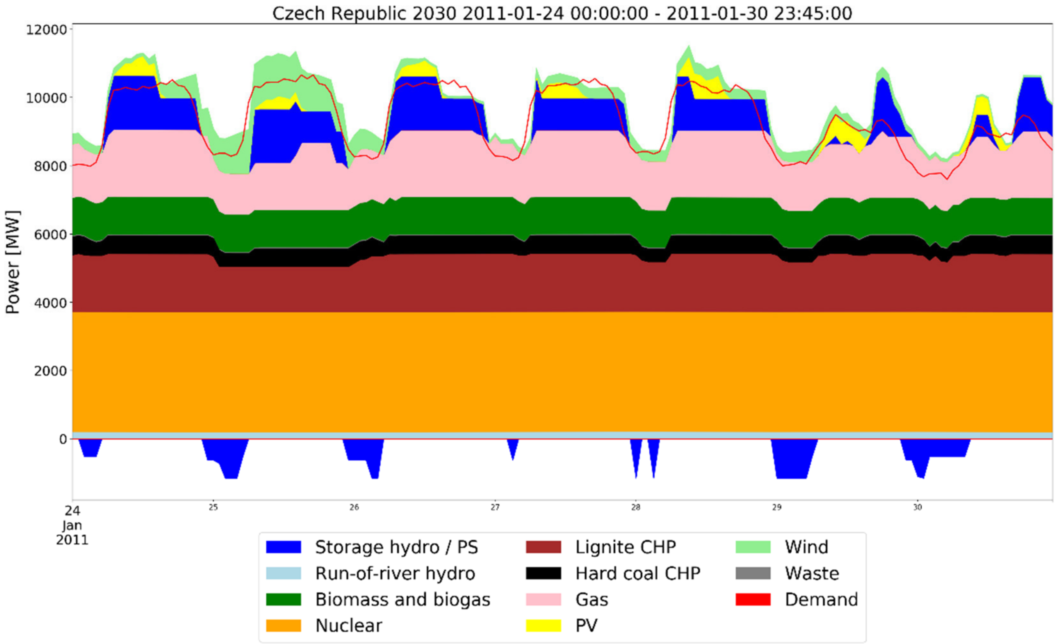

Figure 3: Dispatch in the Czech Republic, baseline scenario without grid reinforcements, January week. (Source: Simulation results.)

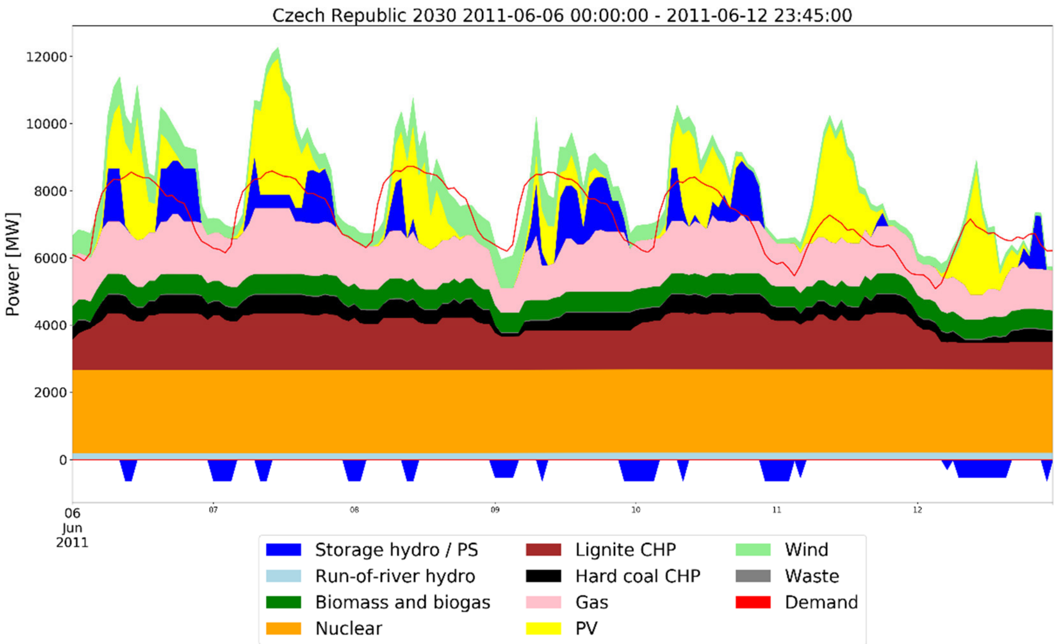

Figure 4: Dispatch in the Czech Republic, baseline scenario without grid reinforcements, June week. (Source: Simulation results.)

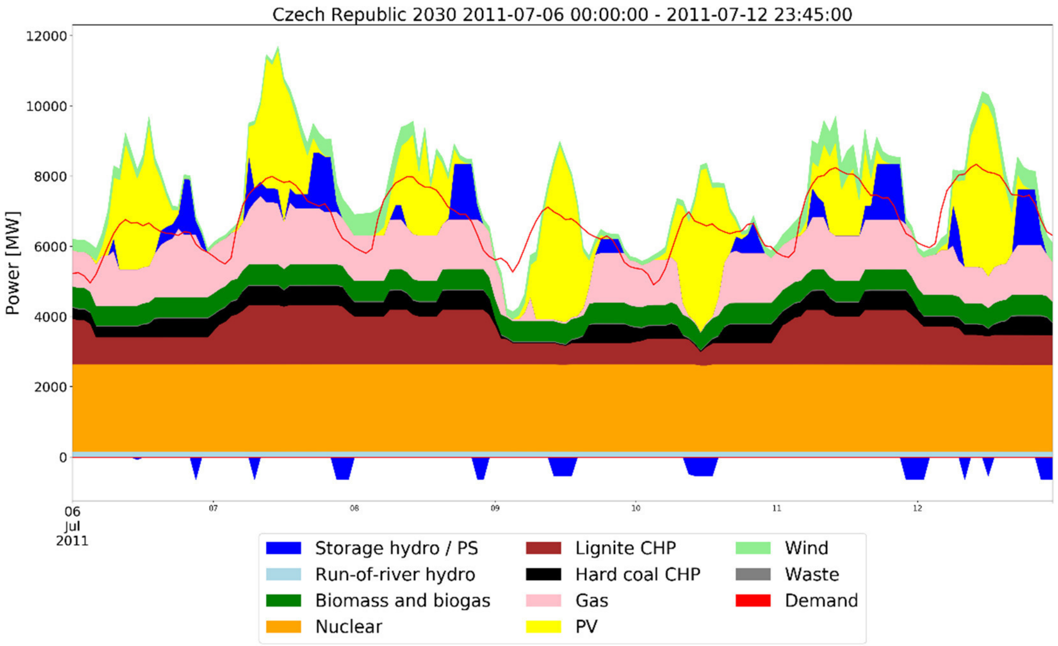

Figure 5: Dispatch in the Czech Republic, baseline scenario without grid reinforcements, July week. (Source: Simulation results.)

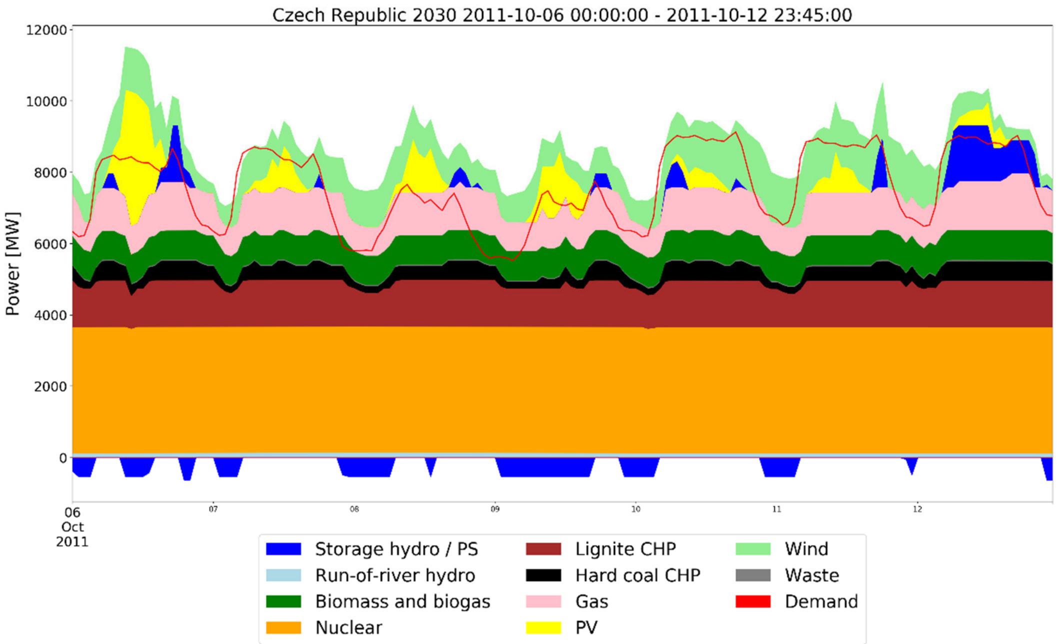

Figure 6: Dispatch in the Czech Republic, baseline scenario without grid reinforcements, October week. (Source: Simulation results.)

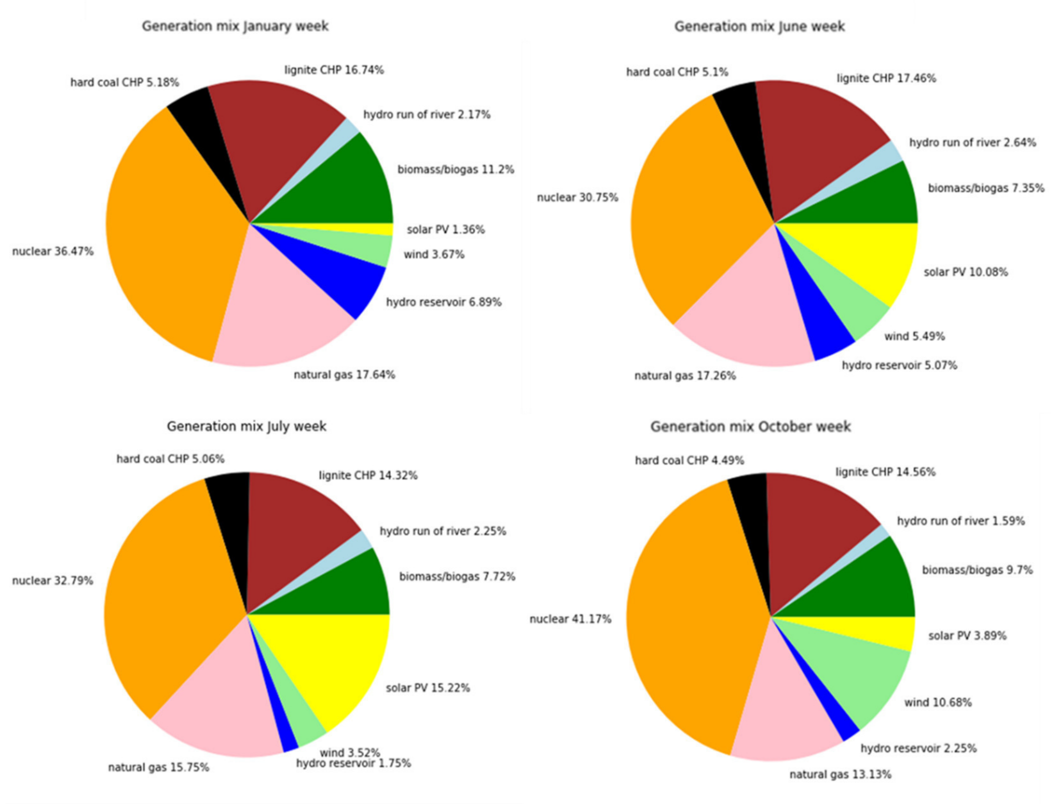

Figure 7: Weekly generation mixes for all four example weeks. (Source: Simulation results.)

2.2.4 Study Case: Extreme Winter

We modelled the grid load for the coldest two weeks, assuming an average temperature below -15° C. Based on the corresponding daily average temperatures for the 2011 measured load, under the current assumptions (65 TWh demand + 4 TWh losses annually), daily consumption would under such circumstances rise to above 250 GWh per day on week days (see extrapolation in Figure 8). This value was entered into the model, with three weeks with very low wind contribution in late February and early March chosen as the model case for very low temperatures. Conditions in neighboring countries were left unchanged for simplicity and lack of detailed data.[5]

[5] The impact of cold weather on electricity demand is highest in the countries with a high share of electric heating. In Europe, these are the Czech Republic, France, Sweden and Norway. The latter three do not significantly impact the Czech system.

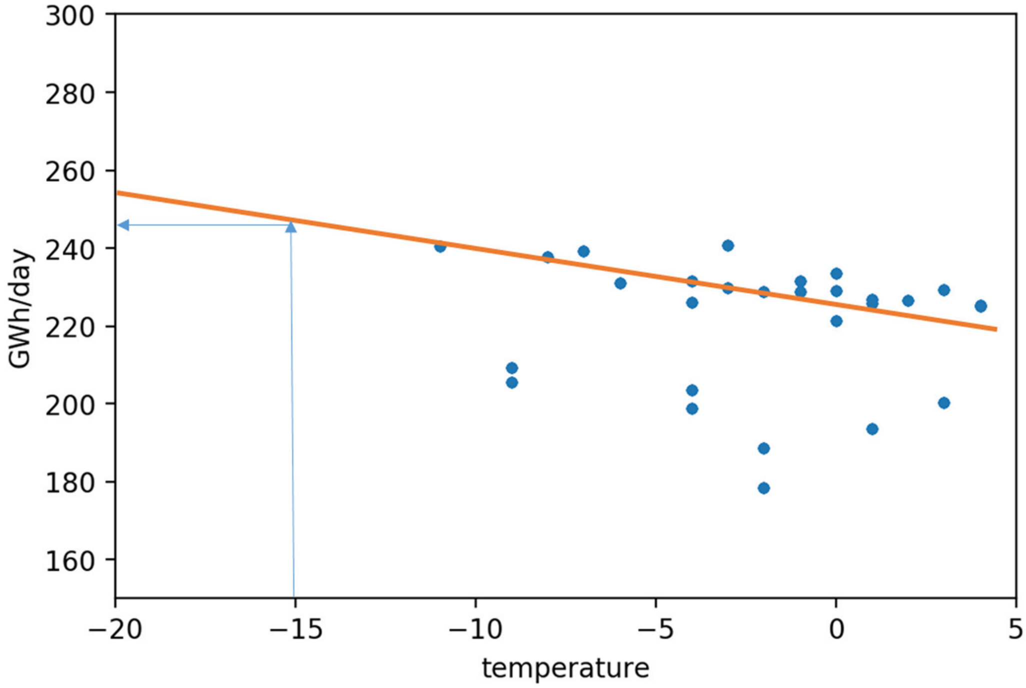

Figure 8: Extrapolation of weekday demand depending on temperature.

For the baseline scenario (and also scenarios B and C), it is assumed that only three of the four blocks at Dukovany are available at all time to account for frequent problems with the old power plant. However, the operator usually strives to have all four blocks running during the coldest weeks of winter. The simulations was thus conducted twice, once with four and once with three blocks available. The results are shown in Figure 9 through Figure 11.

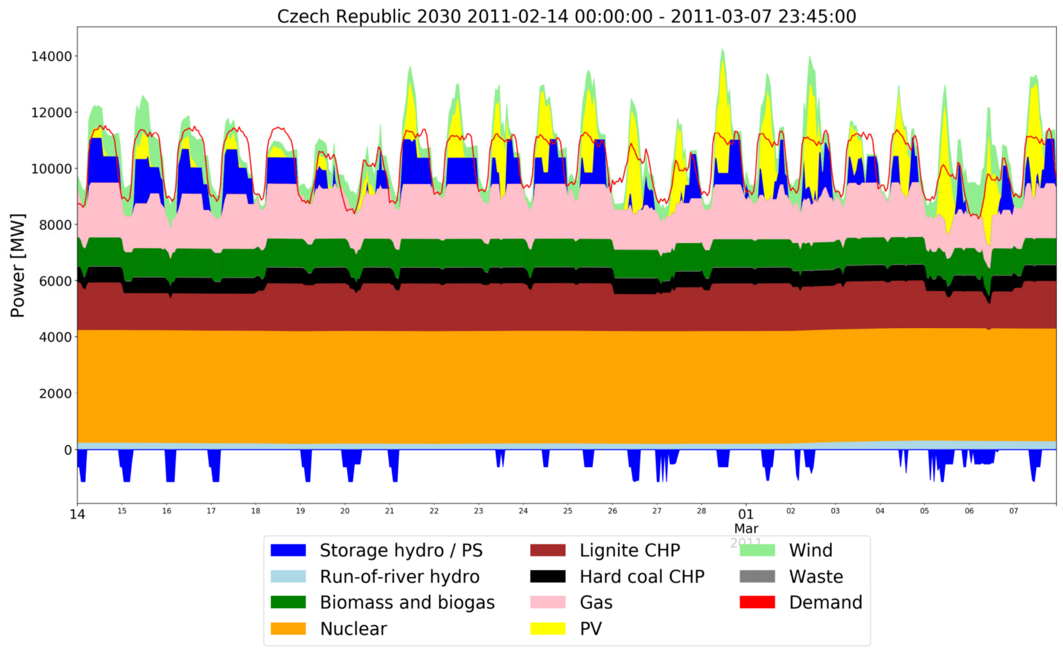

Figure 9: Dispatch in the three coldest weeks with all four blocks of Dukovany running. (Source: Simulation results.)

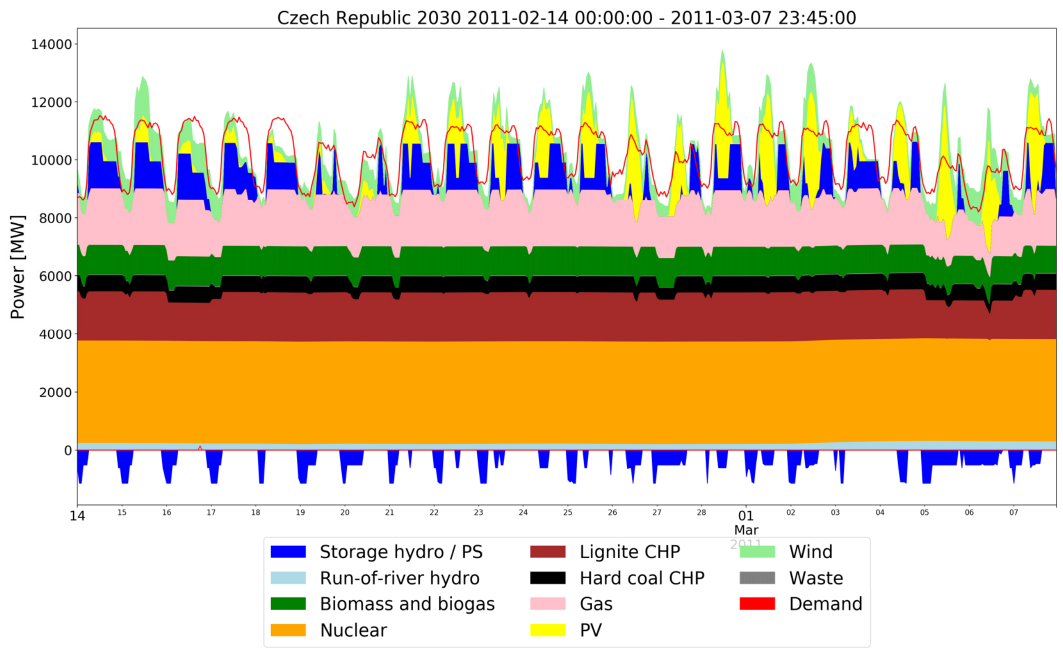

Figure 10: Dispatch in the three coldest weeks with all only three blocks of Dukovany running. (Source: Simulation results.)

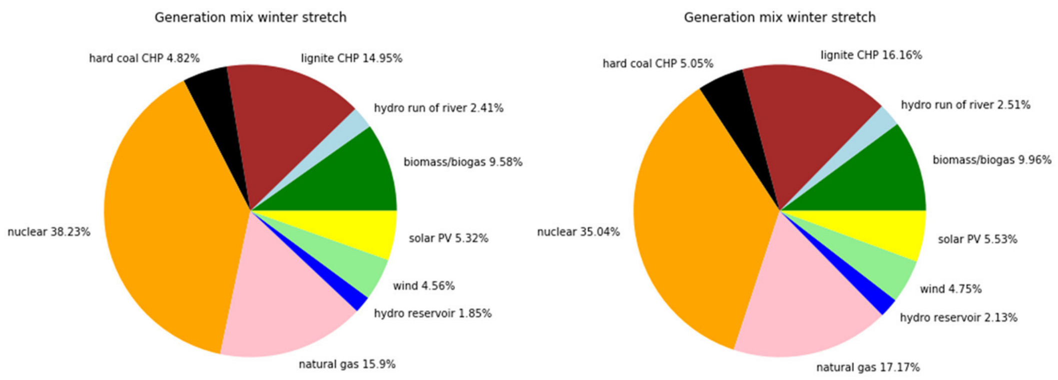

Figure 11: Generation mix for the three weeks, both cases. (Source: Simulation results.)

As the model weeks are late in the winter, solar contribution is already comparably high on some days, while others have virtually no solar. Wind is low for all three weeks. The following can be observed:

- With Dukovany fully operational (Figure 9), load can be covered domestically even without PV, however, coal units are not always fully utilized. With the PV contribution present, the Czech Republic still exports during the day.
- With only three blocks operating, the most obvious differences are the flat out full power operation of almost all coal units, and the increase in pumped storage activity. More water has to be pumped during lower load and PV feed-in times to cover the high daily load. The system operates very close to its capacity maximum, however, whenever PV is available, power is still exported.
- In both cases, all CHP units (gas, coal and biomass/biogas) are constantly running at full output, only in some cases slightly decreasing output during the night.

While there is no critical shortage in either case, the system is rather dangerously close to its firm capacity limit. Non-availability of hydro (water freezing) or coal units, which may experience issues with fuel supply during very cold periods, would lead to a shortage. It can be covered through imports, however, it may be advisable to have around 1 GW of cold reserve plants as a backup for such periods, akin to the cold reserves activated in Austria and Germany activated in some winters in the past decade.[6]

Cold reserve plants are typically older units that are mothballed and can be reactivated with a couple of days or weeks of lead time. In Germany and Austria, these are mostly older gas or oil fired units that cannot operate profitably in the market any more. Grid operators pay to keep these units in working condition to reactivate them when needed. In Germany, the typical reason for starting up reserve units is not general a lack of operating capacity in the German-Austrian zone, but preventive redispatch. Demand in south Germany is high in winter, while for long stretches of time with high wind, most of the

[6] http://www.germanenergyblog.de/?p=11269

power is generated in the north. As the HVDC corridors connecting Germany have not yet been built, grids tend to be overloaded, requiring some redispatch to the south.

3. SCENARIO A: DUKOVANY DECOMMISSIONED

3.1 SCENARIO

Scenario A is used to determine the impact of an early decommissioning of the Dukovany nuclear power station (before 2030). The nuclear power station of Dukovany consists of four pressurized water reactors of the Soviet type VVER-440/213. These units are optimized for baseload operation and have a net installed capacity of 471 MW each (510 MW of gross capacity), resulting in a total of 1884 MW of usable installed capacity in the power station. The units were commissioned between 1985 and 1987. Dukovany feeds around 12 TWh into the Czech grid annually, corresponding to a contribution of 15-17 % of Czech net generation. Average capacity factor is expected to be around 75 % in the future, slightly higher than the operational results from 2014-16 where the plant experienced frequent technical problems, but lower than the 85 % maximum reached in the past due to the aging of the units. In the baseline scenario, this was simulated in a simplified way by having one block always offline, resulting in a usable capacity of 1413 MW and an annual production of 12.38 TWh.[7]

The following simulations were conducted:

- Dukovany decommissioned, not replaced with other capacity increases;
- Dukovany decommissioned and replaced with a total of 2 GW of capacity, 1200 MW of biomass and biogas (60 % capacity factor) and 800 MW of CCGT (installed at the old substation in Dukovany), resulting in on average 1520 MW of usable capacity to replace Dukovany's average of 1413 MW.

The additional biomass generation was distributed across the country in the same way the original capacities were distributed. Parts of the capacity could be implemented by capacity increases in existing units, or by retrofitting older coal units. As with the original capacities, it is assumed that around two thirds of generation come from solid biomass (wood) and the rest from biogas.

To provide sufficient supply of biomass for the assumed renewables development, it is clear that it would be necessary to use biomass intently grown on agricultural land (forest biomass is currently completely used for heating). The necessary supply of biomass as a primary fuel for electricity production is currently appx. 20 PJ of biomass (2,1 TWh excluding biogas).[8] The baseline biomass development according to RES Chamber for 2030 will

[7] It should be noted that this study does not consider Dukovany to have only three blocks. It is a simplification to simulate the 75 % average capacity factor (75 % of the capacity, i.e. three blocks, are always available).

[8] https://www.mpo.cz/assets/cz/energetika/statistika/obnovitelne-zdroje-energie/2018/2/Obnovitelne-zdroje-energie-v-roce-2016.pdf.

need appx. 20 PJ more. Scenario B with Dukovany off and additional 1200 MW of biomass will need appx. 50 PJ more, adding up to 90 PJ total.

Potential of actually unused arable land[9] could cover 68 PJ, part of which would be used for the planned biogas plants development. Additional potential is in straw from cereal production - 50 PJ for energy use of 50 % of straw. There are two more options to change status quo on biomass field: 1) replace rape for biofuels (rape currently covers 400,000 ha of arable land) with more efficient energy plants and 2) save some wood from households heating (74 PJ currently) and use it in power plants (both options would be rather difficult in practice).

3.2 RESULTS

3.2.1 Energy Balances

As visible in Table 5, shutting down Dukovany without replacing it would, under assumptions otherwise unchanged from the baseline scenario, result in the Czech Republic becoming a net electricity importer. Moreover, peak demand can no longer be covered domestically at all times. This mandates the replacement of the unit with other firm generating capacity, resulting in Scenario A.

Under this scenario, without any grid reinforcements, CZ remains a net electricity exporter, albeit only slightly so. With optimized reinforcements in the European grid, CZ becomes a net importer – cross border capacities and bottlenecks in neighboring countries are reinforced, and it is simply cheaper to import coal or wind power from abroad than to run the 800 MW of CCGT during most times. The 12 TWh from Dukovany (75 % average capacity factor[10]) are partially replaced domestically – 8.3 TWh without reinforcements, only 6.9 TWh with reinforcements – while the rest is being imported.

This is a logical result, as the cheap baseload generation of Dukovany is partially replaced with more expensive gas fired generation. The firm generating capacity of the system is unaffected, CZ can cover its peak demand domestically if necessary. The Czech Republic still exports a considerable amount of power during low demand (cheap power from biomass, CHP and remaining nuclear) and high VRE availability, while mainly importing during peak hours.

[9] The unused arable land is an area of 500,000 ha - http://www.apic-ak.cz/definitivni-udaje-o-sklizni-zemedelskych-plodin-2017.php)

[10] Lower value of factor in comparison with the historical average is used with respect to low experience with operation of 45 years old blocks (first block in Dukovany was commissioned in 1985).

Table 5: Import / export balances in TWh.

	Original scenario		**Dukovany off**	**Dukovany replaced (Scenario A)**	
	No reinforce-ments	Optimized reinforce-ments	Optimized reinforce-ments	Optimized rein-forcements	No reinforce-ments
Demand	65 TWh	65 TWh	65 TWh	65 TWh	65 TWh
Losses	4 TWh	4 TWh	4 TWh	4 TWh	4 TWh
Net generation	72.99 TWh	71.25 TWh	63.04 TWh	65.87 TWh	69.29 TWh
Imports	1.42 TWh	2.16 TWh	6.94 TWh	4.97 TWh	2.95 TWh
Exports	5.40 TWh	4.41 TWh	0.98 TWh	1.83 TWh	3.24 TWh
Balance	3.99 TWh	2.25 TWh	-5.96 TWh	-3.13 TWh	0.29 TWh

In both cases, the electricity mix experiences a shift towards a higher share from biomass and gas fired generation compared to the baseline scenario (Figure 12). However, even with 800 MW of new CCGT in the system, the contribution of natural gas rises only slightly, as it is often cheaper to import power from neighboring countries than to use domestic gas fired units. This is especially the case with grid reinforcements that largely eliminate import restrictions. On the other hand, the higher gas fired capacities lead to a lower contribution from hydro reservoirs (which leaves these capacities as a reserve for contingencies) as CCGT units are often cheaper than peaking hydro plants.

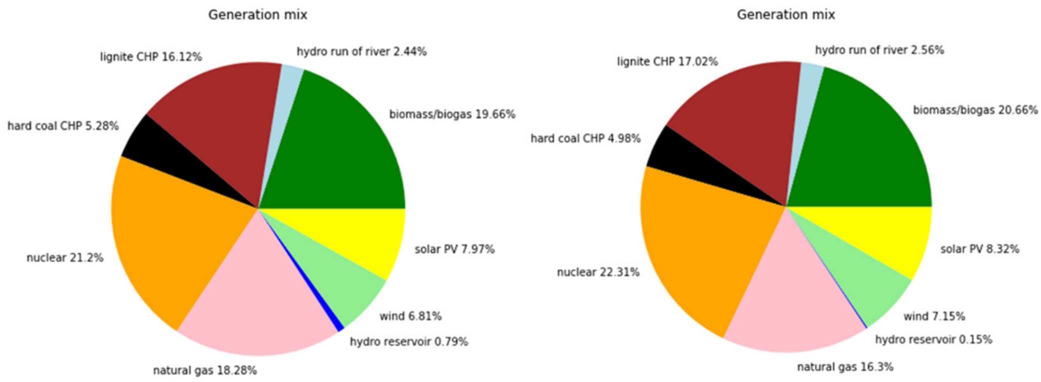

Figure 12: Generation mix by fuel source, Scenario A without (left) and with (right) reinforcements. (Source: Simulation results.)

This becomes clearer when analyzing the capacity factors of each technology, given in Table 6. Without grid reinforcements, the capacity factor for CCGT units drops slightly, but as installed capacities are higher, the overall contribution is higher. With grid reinforcements, the average CCGT capacity factor drops to 21.65 %, which leaves the units at the lower threshold of economical operation (typically, CCT units can operate profitably above 2000 full load hours, which corresponds to a capacity factor of 22 %).

Other expensive peaking plants, such as the especially the open gas turbines (of which only 170 MW are installed in the Czech system),[11] also reduces their capacity factors with grid reinforcements. Without Dukovany and with a reinforced grid, price differences between night and day are also lower, so that the utilization of pumped storage plants is lower.

Table 6: Annual capacity factors by technology.

Technology	Baseline scenario		Scenario A	
	without reinforcements	w/ optimized reinforcements	without reinforcements	w/ optimized reinforcements
Biomass and biogas	60.07%	60.11%	60.14%	60.11%
Natural gas CCGT	37.90%	33.08%	30.27%	19.24%
Natural gas small CHP	92.86%	92.51%	93.14%	93.51%
Natural gas OCGT	21.09%	0.53%	26.94%	0.02%
Hard coal CHP	72.24%	68.48%	79.11%	71.04%
Hydro PS generation	6.28%	1.80%	6.97%	0.80%
Hydro PS pumping	6.50%	2.23%	5.11%	1.11%
Hydro reservoirs	34.50%	10.62%	15.56%	2.90%
Hydro run of river	53.13%	53.08%	53.09%	53.08%
Lignite CHP	72.65%	72.76%	75.05%	75.33%
Nuclear Dukovany	74.99%	74.99%	-	-
Nuclear Temelín	79.46%	79.48%	79.48%	79.48%
PV	11.47%	11.47%	11.47%	11.37%
Waste incineration	99.97%	99.98%	99.98%	99.97%
Wind	26.22%	26.23%	26.27%	26.22%

3.2.2 Reinforcements

Under Scenario A, grid reinforcements in the Czech Republic are not strictly necessary for system stability, but are introduced for economic reasons – they allow for more imports from abroad at rising domestic peak power prices incurred by the decommissioning of Dukovany. This is clearly reflected in the results (Table 7), which determine the need for reinforcements mainly on cross border lines. A large part of grid reinforcements is also

[11] There are three open cycle gas turbines in the Czech system, Kladno I+II and the Prostejov peaking plant. http://www.alpiq.cz/en/what-we-offer/our-assets/thermal-power-plants/combined-cycle-power-plants/elektrarna-kladno-I.jsp, http://www.alpiq.cz/en/what-we-offer/our-assets/thermal-power-plants/combined-cycle-power-plants/elektrarna-kladno.jsp, http://www.gamainvestment.cz/en/energetika

(partially) driven by the Polish dependency on imports, reinforcing the corridor between Slovakia and Poland. The reinforcement of this corridor facilitates Czech transactions with both countries, often importing from Slovakia and exporting to Poland.

This leaves the Czech grid in a situation somewhat similar to the Swiss grid, which is a main hub for flows between France, Italy and Germany. To a certain degree, this is already the case today, with the transfer and loop flows introduced by trades between Germany and Austria are the main reason for the installation of phase shifting transformers (PST) in the Hradec substation (and on the Polish border as well). The increase in cross-border flows and the resulting higher utilization of the grid is a side effect of European market integration and the increase in VRE generation that can also be observed in the Benelux countries. This shows that an integrated European approach to grid planning and reinforcements is necessary. Grid reinforcements are not necessarily driven only by the development inside a country, but also by transitions in the neighboring countries, and benefit all involved parties. Currently, European grid projects are specified in the Ten Year Network Development Plan (TYNDP), which is not a coordinated plan, but largely a collection of projects of the individual grid operators. The cost/benefit question of new grid projects, as in who pays for it and who profits, is currently an issue that is greatly discussed also within ENTSO-E. In a meshed grid with an integrated European market, these questions can become quite complex and will require additional efforts in analysis and multilateral agreements by the transmission system operators.

The Czech Republic benefits from this reinforcement since its own import and export capacities also increase, reducing the overall cost of electricity in the country.

Table 7: Grid reinforcements in CZ, Scenario A.

Line	Action	Impact
Border CZ-PL (Nosovice-PSE)	Two new 400 kV circuits on the lines from Nosovice to the PSE grid (Dobrezen, Wielopole, Kopanina or Bujaków)	Corridor Slovakia-CZ-Poland
Border CZ-SK (Nosovice)	Two new 400 kV circuits on the lines from Nosovice to Varín (SK)	Corridor Slovakia-CZ-Poland
400 kV line Sokolnice-Prosenice	Additional 400 kV circuit	Corridor Slovakia-CZ-Poland
220 kV line Sokolnice-Prosenice	Upgrade of double circuit line to 400 kV	Corridor Slovakia-CZ-Poland
400 kV line Sokolnice-Bohunice (SK)	Additional 400 kV circuit	Corridor Slovakia-CZ-Poland
400 kV line Sokolnice-Stupava (SK)	Two additional 400 kV circuits	Corridor Slovakia-CZ-Poland

Compared to the baseline scenario, less reinforcements on the Czech-Polish interconnector are needed. The reason are less exports from the Czech Republic, also freeing the corridor for other transactions. However, Slovakia exports more power to the Czech Republic and Poland (via CZ), so more line capacity is needed on the South-Eastern border.

3.2.3 Dispatch Examples

The dispatch examples for the same weeks as in the baseline scenario are given in Figure 13 through Figure 16 for comparison. Gas and biomass contribution is slightly higher to compensate for the loss of the nuclear unit, coal power plants have to load follow less often. Weekly generation shares are given in Figure 17.

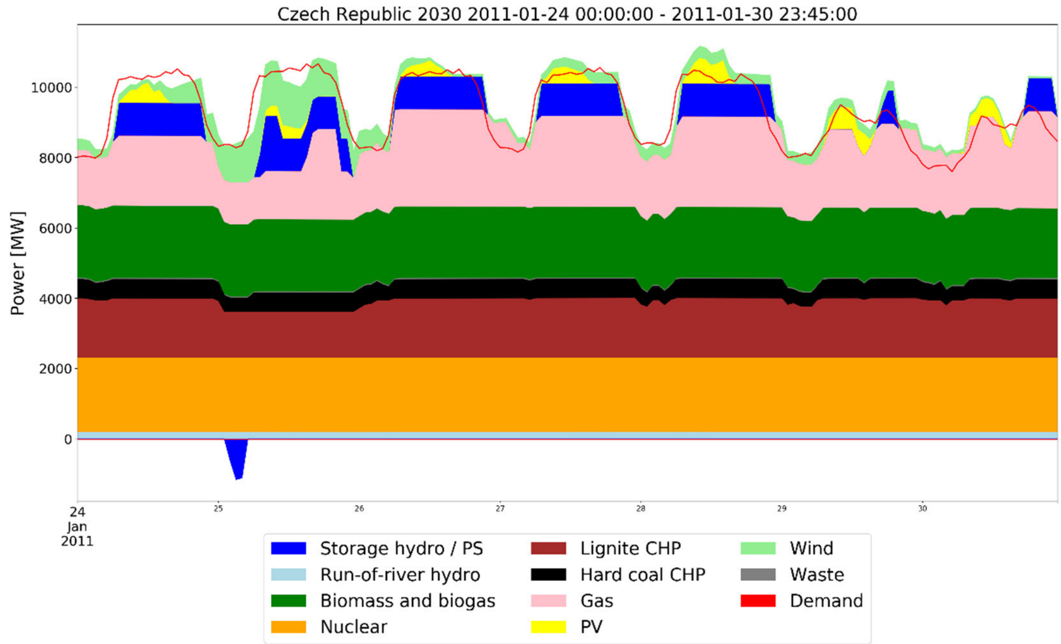

Figure 13: Dispatch in the Czech Republic, Scenario A without grid reinforcements, January week. (Source: Simulation results.)

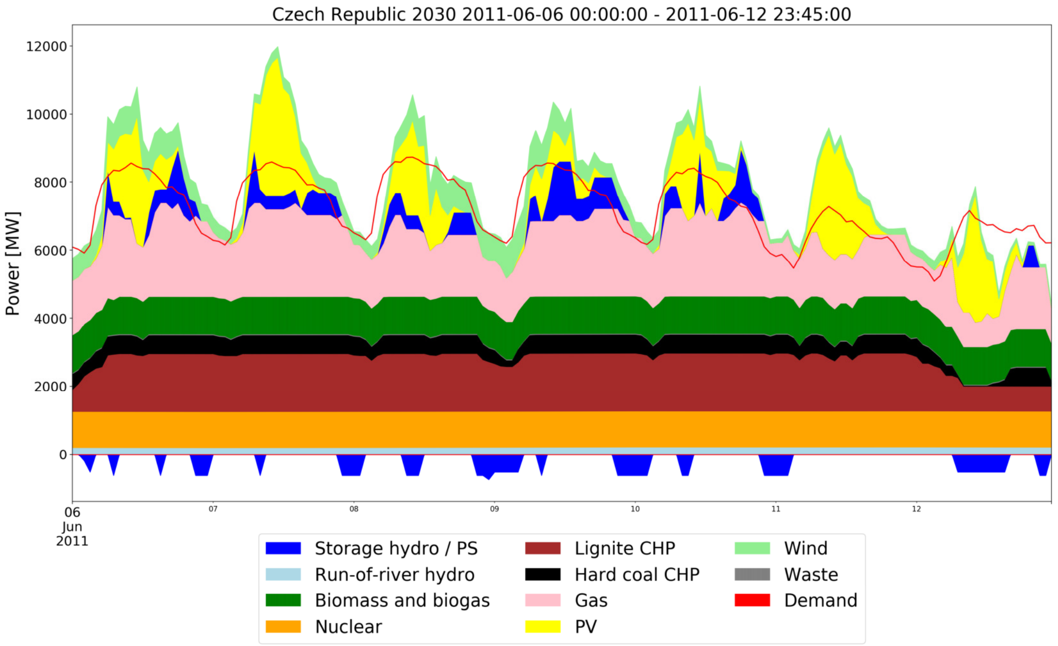

Figure 14: Dispatch in the Czech Republic, Scenario A without grid reinforcements, June week. (Source: Simulation results.)

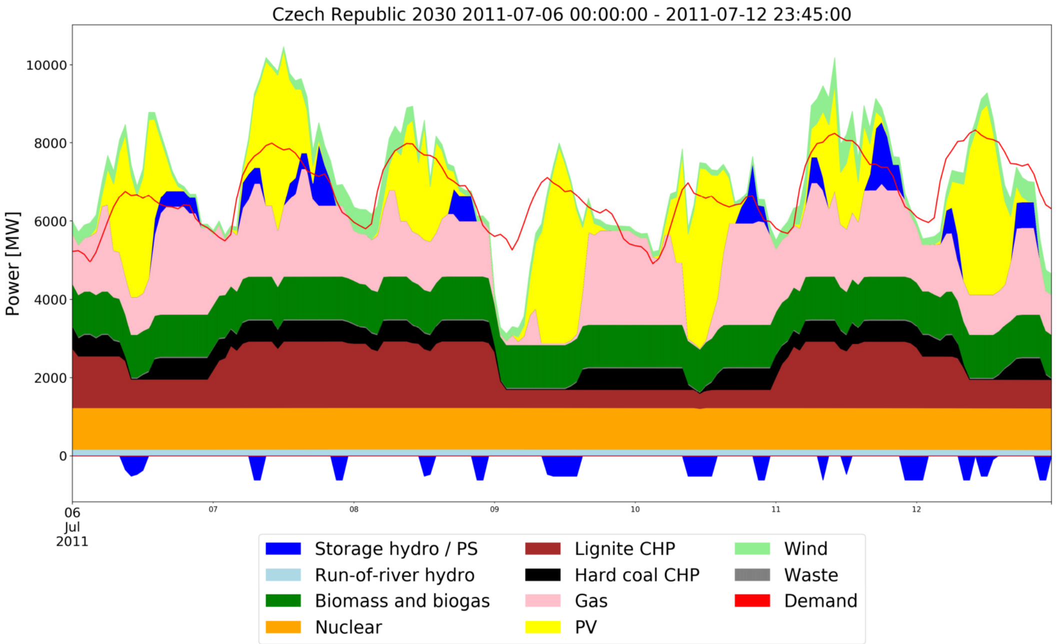

Figure 15: Dispatch in the Czech Republic, Scenario A without grid reinforcements, July week. (Source: Simulation results.)

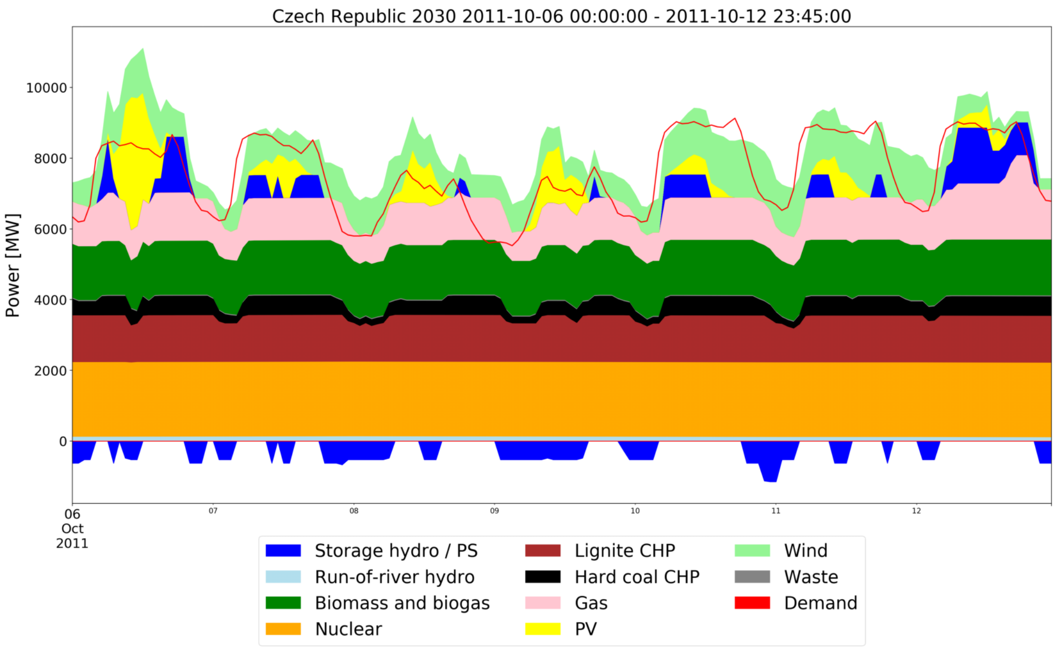

Figure 16: Dispatch in the Czech Republic, Scenario A without grid reinforcements, October week. (Source: Simulation results.)

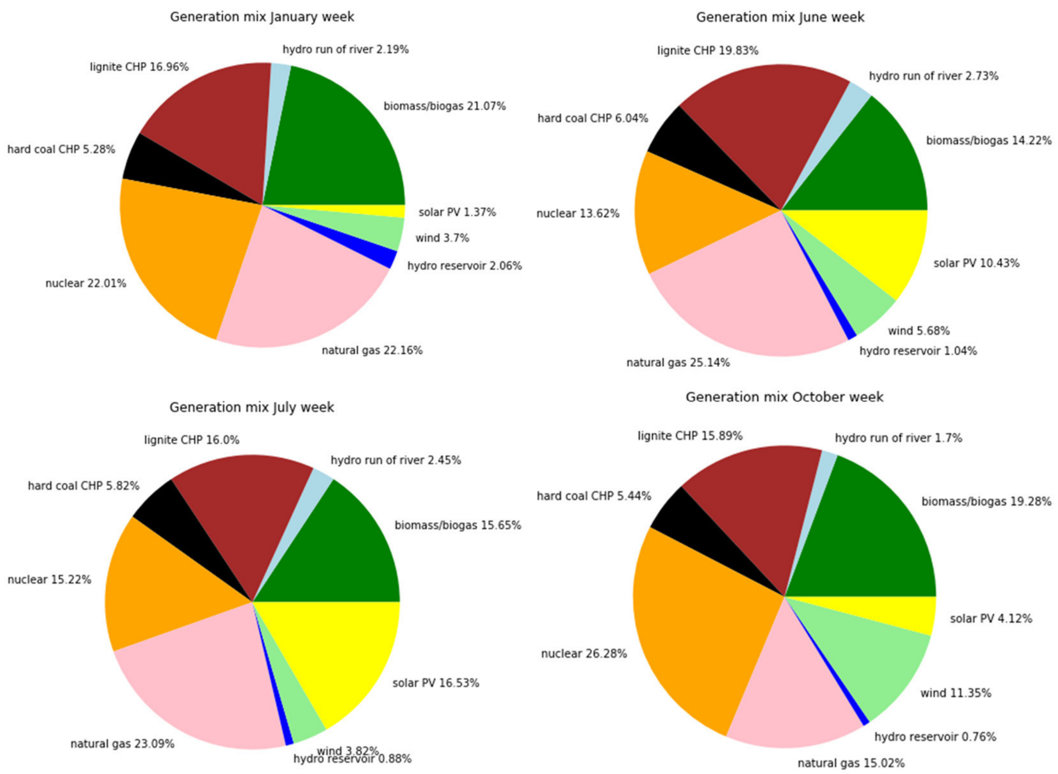

Figure 17: Weekly generation mixes for all four example weeks. (Source: Simulation results.)

4. SCENARIO B: REDUCED IMPORT

4.1 SCENARIO

Scenario B retains the same capacities and operational procedures for the Czech system as the baseline scenario, but assumes a less optimistic development in Poland and Germany. Under this scenario, Poland retires some of its coal fleet according to the scenario set out in the Forum Energii report[12] on Polish development between 2030 and 2050 and relies mostly on wind and power imports to replace it. Germany implements a partial coal exit with high wind and PV capacities as set forth in Scenario B ("National Green Transition") from the 2017 German Network Development Plan.[13] France retires 20 GW of its nuclear fleet according to its official plans, but does not replace it with firm capacity right away, relying on German imports. This draws German export capacities to the West, which strongly reduces capacities for export to the Czech Republic.

Scenario B has the following additional properties from the original scenario:

- Polish coal capacities are decreased to 12 GW of hard coal and 5 GW of lignite, gas CCGT capacities increased to 5 GW, wind to 15 GW and PV to 5 GW;
- French nuclear capacities are reduced from 63 to 43 GW (based on remaining lifetime of currently installed units), moreover, the system has 8 GW of gas, ca. 20 GW (not firm) of hydro as well as some oil fired reserve capacities, leaving France with a capacity shortage in winter. Renewables: 31 GW of wind, 9 GW of PV;[14]
- Germany is in the "National Green Transition" with strongly reduced coal capacities (9.5 GW lignite, 14.8 GW hard coal, down from 21 / 28 GW today), 38 GW of natural gas. Nuclear power has been phased out, and 58.5 GW of wind onshore, 15 GW of wind offshore, 66.3 GW of PV and 6.2 GW of biomass/biogas are installed in the system.[15]

This leaves the Czech Republic in the situation that it can a) not always rely on imports, b) needs to support the Polish system and c) can be expected to increase power exports.

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[12] http://forum-energii.eu/pl/news/miks2050raport.html

[13] The German NDP 2017 still contained a baseline scenario with high coal capacities, which was used for the baseline scenario in this study, and a transition scenario as described here. The 2019 iteration of the NDP, the scenarios for which are being discussed as of August 2018, will most likely not contain a high coal scenario any more.

[14] Renewable capacities from baseline scenario of Greenpeace Energy Revolution, based on the actual government plans: https://www.greenpeace.de/files/publications/201402-power-grid-report.pdf

[15] English presentation on the NDP scenarios 2017: https://www.netzentwicklungsplan.de/sites/default/files/paragraphs-files/170606_Basispr%C3%A4sentation_NEP_2030_2_Entwurf_eng.pdf

4.2 RESULTS

4.2.1 Energy Balances

The following patterns can be observed from the results:

- Poland dependent on imports during peak hours with low wind, but exports a lot of wind during high wind feed-in;
- France keeps exporting to Italy in summer, but is dependent on imports from Germany in winter;
- Germany exporting during high wind, importing during low wind, like today, with the majority of transactions going to Poland and France.

This results in an overall increase in exports from the Czech Republic, as visible in Table 8. Exports are, as usual, lower with grid reinforcements, as importing countries have access to more diverse suppliers by the strengthening of interconnector capacities.

Table 8: Import / export balances.

	Original scenario		Scenario B	
	No reinforce-ments	Optimized re-inforcements	Optimized rein-forcements	No reinforce-ments
Demand	65 TWh	65 TWh	65 TWh	65 TWh
Losses	4 TWh	4 TWh	4 TWh	4 TWh
Net generation	72.99 TWh	71.25 TWh	73.11 TWh	76.24 TWh
Imports	1.42 TWh	2.16 TWh	1.43 TWh	0.63 TWh
Exports	5.40 TWh	4.41 TWh	5.58 TWh	7.87 TWh
Balance	3.99 TWh	2.25 TWh	4.11 TWh	7.24 TWh

The capacity factors in Table 9 clearly exhibit the Czech Republic's new role as an exporter not only of cheap baseload and renewable power (which it was already under the baseline scenario), but also as an exporter of intermediate and peaking power. CCGT generation is increased by 45 %, hard coal generation by 18 %, while the short time peaking plants (OCGT) double their capacity factors. Under this scenario, it would make sense to install even more CCGT units in the Czech Republic to offer more cheap intermediate and peaking power. The resulting generation shares are given in Figure 18.

Table 9: Annual capacity factors by technology.

Technology	Baseline scenario		Scenario B	
	without rein-forcements	w/ optimized reinforcements	without rein-forcements	w/ optimized reinforcements
Biomass and biogas	60.07%	60.11%	60.11%	60.14%
Natural gas CCGT	37.90%	33.08%	53.92%	40.64%
Natural gas small CHP	92.86%	92.51%	94.11%	94.20%
Natural gas OCGT	21.09%	0.53%	43.50%	0.27%
Hard coal CHP	72.24%	68.48%	84.10%	76.83%
Hydro PS generation	6.28%	1.80%	5.19%	1.96%
Hydro PS pumping	6.50%	2.23%	4.94%	1.78%
Hydro reservoirs	34.50%	10.62%	39.10%	7.65%
Hydro run of river	53.13%	53.08%	53.12%	53.08%
Lignite CHP	72.65%	72.76%	78.21%	77.44%
Nuclear Dukovany	74.99%	74.99%	74.99%	75.00%
Nuclear Temelín	79.46%	79.48%	79.49%	79.50%
PV	11.47%	11.47%	11.46%	11.47%
Waste incineration	99.97%	99.98%	100.00%	99.98%
Wind	26.22%	26.23%	26.19%	26.25%

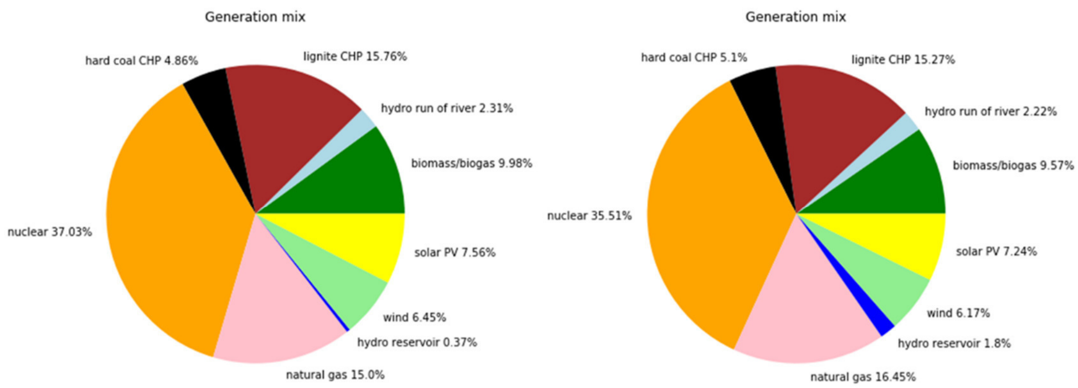

Figure 18: Generation mix by fuel source, Scenario B without (left) and with (right) reinforcements. (Source: Simulation results.)

4.2.2 Reinforcements

Interestingly, the high-VRE scenarios in the surrounding countries lead to less grid expansion in the Czech Republic (see Table 10). The reason is that Poland is more dependent on imports while Czech Republic imports less from Slovakia. In the baseline scenario, grid expansion in the south eastern Czech Republic would form a reinforced corridor with which both Poland and Czech Republic could access Slovak baseload capacities. The load sink in southern Poland, caused by the decommissioning of a number of coal units, makes a direct reinforcement of lines from Slovakia to Poland a better solution in Scenario B.

With transfer flows from Slovakia no longer straining the Czech grid, less grid reinforcements are necessary, while existing line capacities are sufficient for direct exports from the Czech Republic to Poland. This highlights the need for European integrated capacity and grid planning, as different developments may require different solutions even in countries not directly affected by the development.

Table 10: Grid reinforcements in CZ, Scenario B.

Line	Action	Impact
220 kV line Sokolnice-Prosenice	Upgrade of double circuit line to 400 kV	Corridor Slovakia-CZ-Poland

4.2.3 Dispatch Examples

The dispatch examples for the same weeks as in the baseline scenario are given in Figure 19 through Figure 22 for comparison. Generally, gas power plants are running much more, and he Czech system exports at almost all times. Weekly generation shares are given in Figure 23.

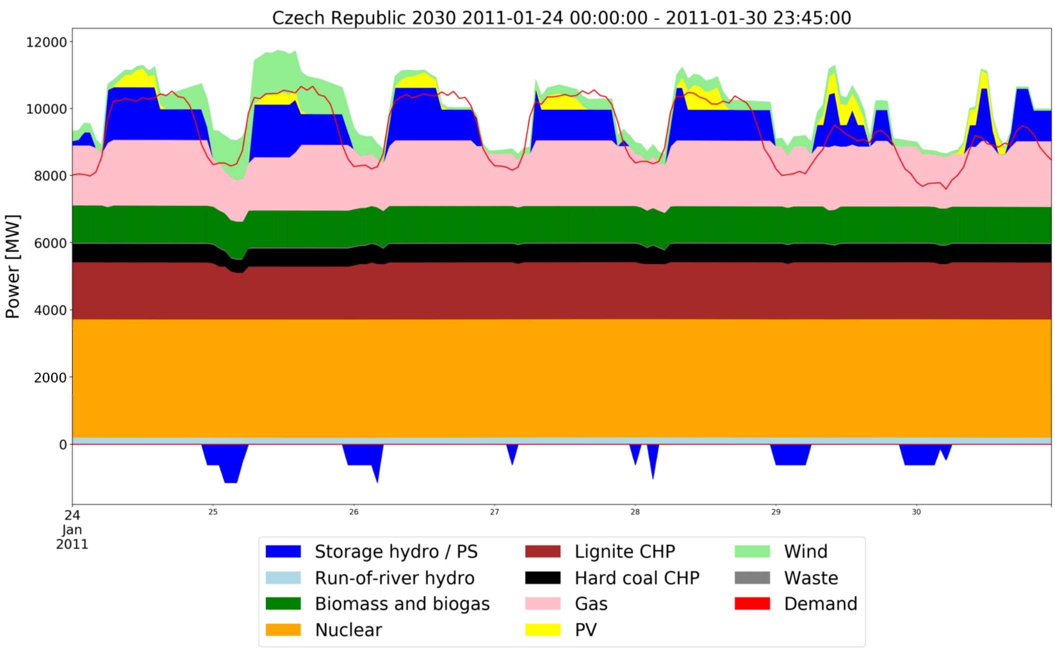

Figure 19: Dispatch in the Czech Republic, Scenario B without grid reinforcements, January week. (Source: Simulation results.)

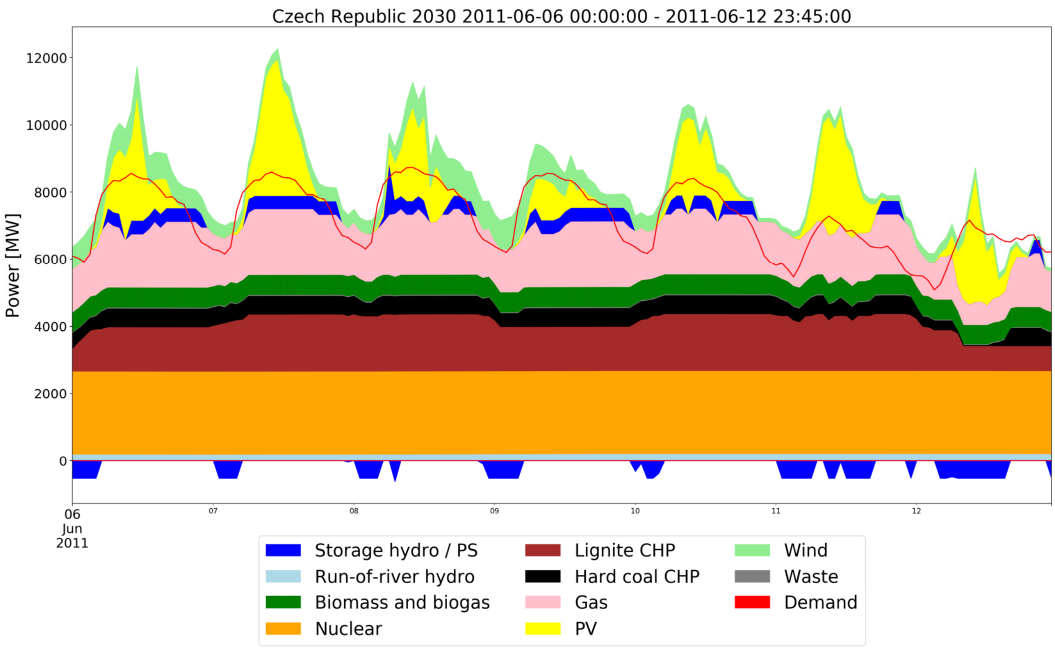

Figure 20: Dispatch in the Czech Republic, Scenario B without grid reinforcements, June week. (Source: Simulation results.)

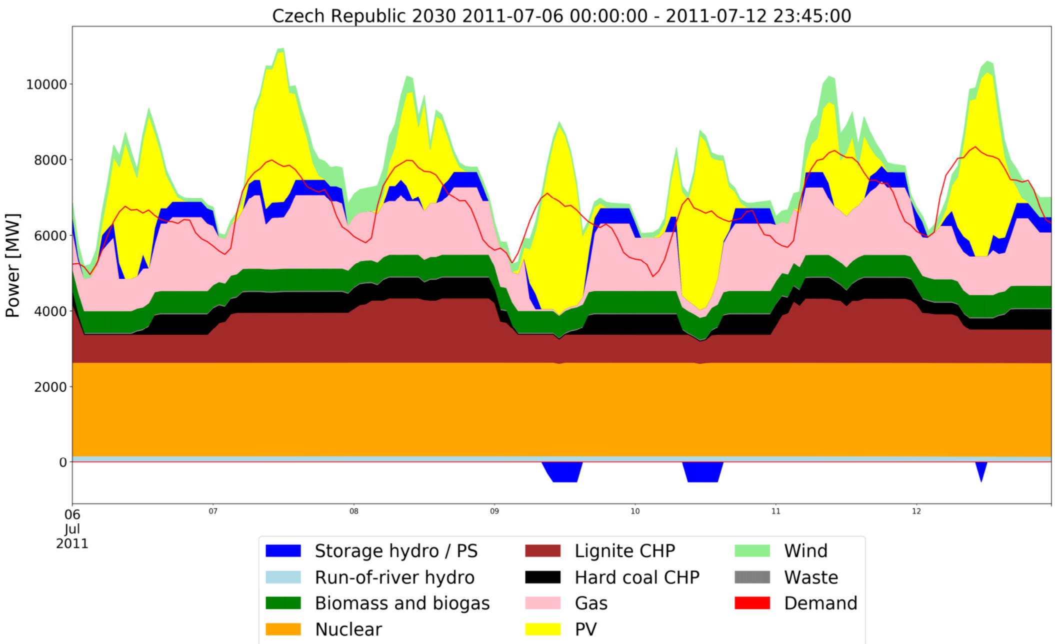

Figure 21: Dispatch in the Czech Republic, Scenario B without grid reinforcements, July week. (Source: Simulation results.)

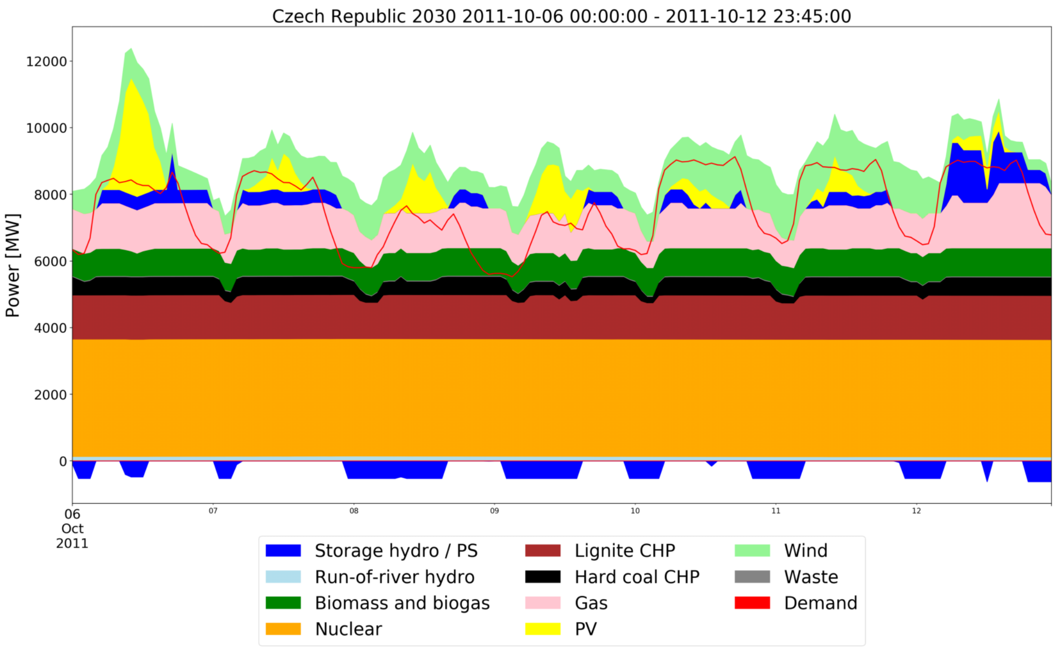

Figure 22: Dispatch in the Czech Republic, Scenario B without grid reinforcements, October week. (Source: Simulation results.)

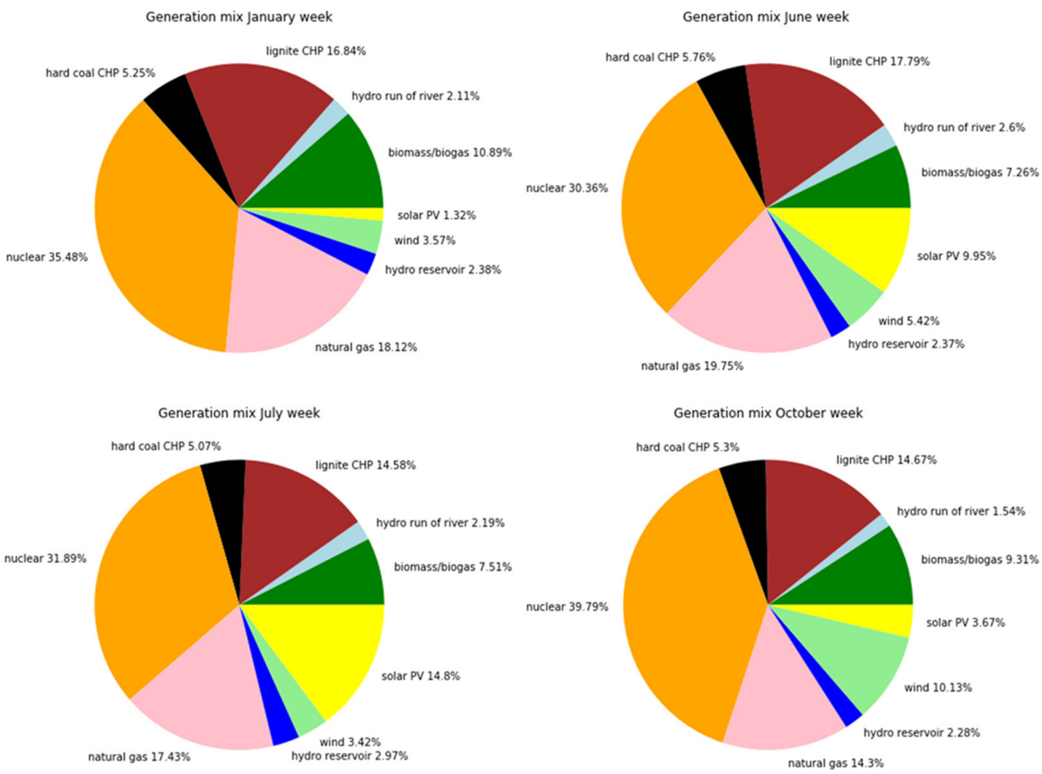

Figure 23: Weekly generation mixes for all four example weeks. (Source: Simulation results.)

4.2.4 Study case: Scenario B without Dukovany (Scenario AB)

As an additional study case, the Czech capacities from Scenario A, with the nuclear power plant Dukovany replaced with gas and biomass units, were combined with the capacities in neighboring countries in Scenario B. Results are shown in Table 11, Figure 24 and Figure 25 (only the critical weeks in winter and autumn are shown as there is little difference in the other examples). Even without Dukovany, the Czech system can still export considerable amounts of power if the market conditions in the neighboring countries call for it. This also shows that new nuclear power plants in the Czech Republic are not necessary for security of supply, and with investment costs in new nuclear units in France, Britain and Finland having skyrocketed,[16] the economic feasibility of new nuclear power plants is generally questionable.

Table 11: Import / export balances.

	Baseline	Scenario A	Scenario B	Scenario AB
	No reinforcements	No reinforcements	No reinforcements	No reinforcements
Demand	65 TWh	65 TWh	65 TWh	65 TWh
Losses[17]	4 TWh	4 TWh	4 TWh	4 TWh
Net generation	72.99 TWh	69.29 TWh	76.24 TWh	70.12 TWh
Imports	1.42 TWh	2.95 TWh	0.63 TWh	2.58 TWh
Exports	5.40 TWh	3.24 TWh	7.87 TWh	3.70 TWh
Balance	3.99 TWh	0.29 TWh	7.24 TWh	1.12 TWh

The Czech Republic also exports power during almost all times, albeit less so than in Scenario B. As visible in the dispatch graphics, the system can cover its load even in winter – but coordinated action from pumped storage plants is required for that. As discussed in section 2.2.4, some more backup capacity may be required here to not become dependent on peak imports during cold weather events. The capacities for such imports however are available in Austria, which operates large overcapacities of fast reacting hydro power plants.

[16] https://www.reuters.com/article/us-edf-nuclear-flamanville/edf-raises-french-epr-reactor-cost-to-over-11-billion-idUSBRE8B214620121203

[17] Estimated based on CEPS experience.

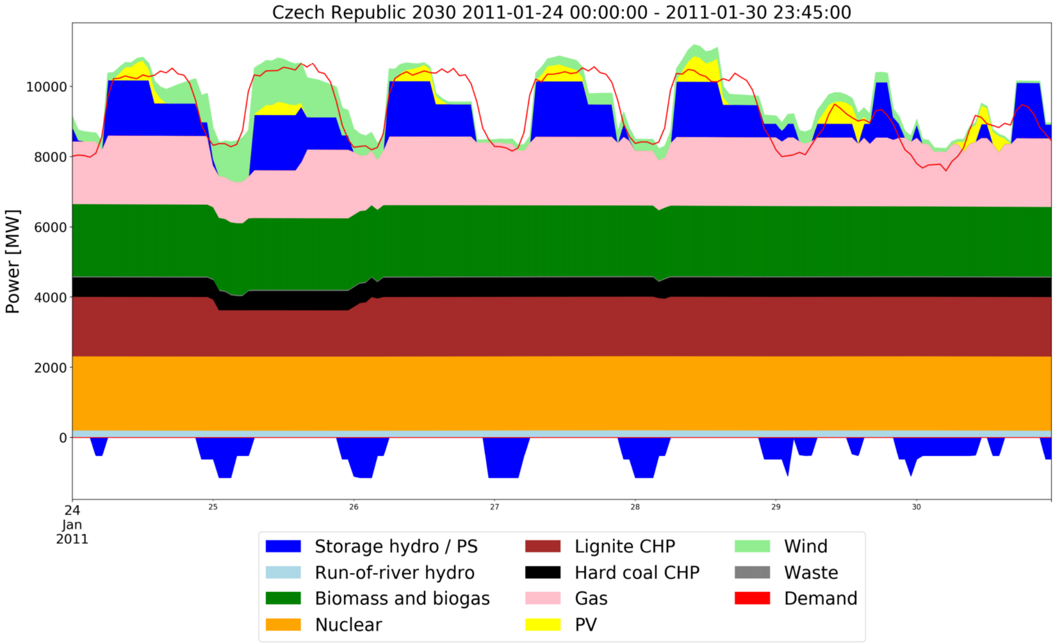

Figure 24: Dispatch in the Czech Republic, Scenario AB without grid reinforcements, January week. (Source: Simulation results.)

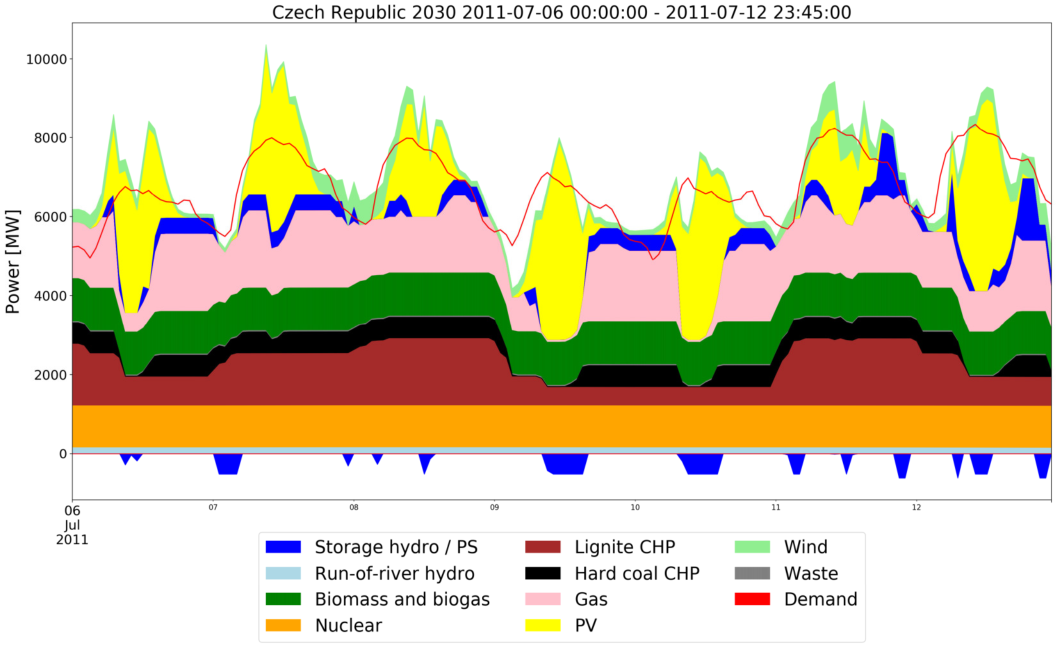

Figure 25: Dispatch in the Czech Republic, Scenario AB without grid reinforcements, October week. (Source: Simulation results.)

5. SCENARIO C: STORAGE, HEAT PUMPS AND EV

5.1 SCENARIO

Scenario C has the following additional properties from the original scenario:

- Load is increased by 3 TWh from heat pumps, demand is added based on a standard load profile for heat pumps by BDEW (German Association of Electricity- and Waterworks).[18] The daily profile is scaled based on a temperature time series obtained from this source[19], which has 2011 weather data from Prague airport publicly available (the year 2011 is chosen because the wind and solar data used is from that year.)
- Load is increased by another 2 TWh from electrical vehicles, a demand profile for 11 kW charging developed by Energynautics based on a previous study is used.
- 50 % of all rooftop PV have an additional battery with a ratio of 0.88 kWh per kWp of installed PV capacity.[20] The battery shaves the peak off the PV feed-in and shifts the power to the evening, smoothening the decrease in PV production in the afternoon and providing additional peak capacity during the evening peak (see Figure 26 and Figure 27). With 2/3 of all PV capacity coming from rooftops, ca. 1500 MWh of storage is installed under the scenario, which is less than 1 % of daily electricity consumption.

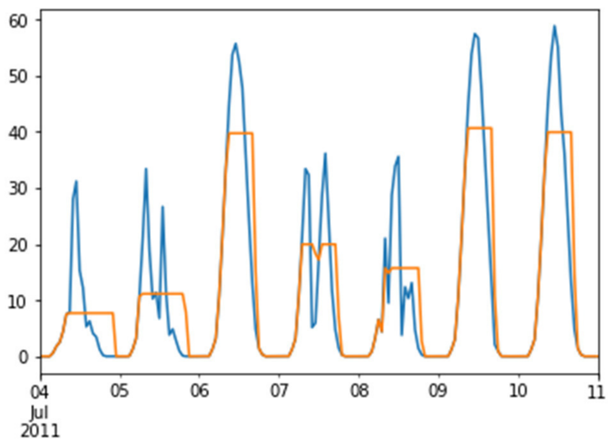

Figure 26: Impact of storage operation on the PV profile (storage equipped rooftop PV only, single node) – PV in blue, PV/storage complex in orange.

[18] This is a standard load profile for an average of different heat pump types. Source: Munich utility company: https://www.swm-infrastruktur.de/strom/netzzugang/bedingungen/waermepumpe.html

[19] https://www.wunderground.com/history/monthly/LKPR/date/2011-1-10

[20] Corresponding with the CZ National Action Plan for Renewables https://www.mpo.cz/cz/energetika/elektroenergetika/obnovitelne-zdroje/

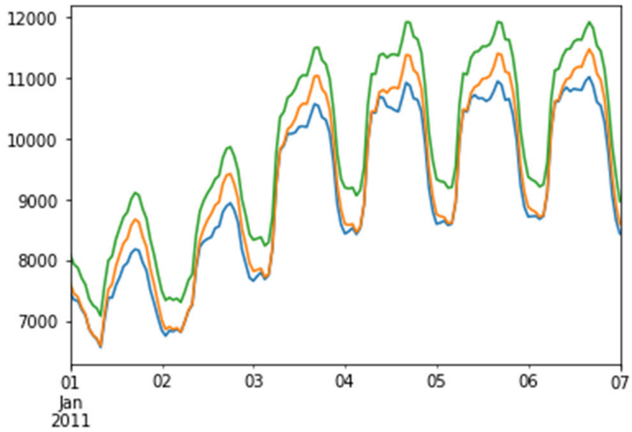

Figure 27: Demand during winter week (blue) with additional demand from EV (yellow) and heat pumps (green).

5.2 RESULTS

5.2.1 Energy Balances

Scenario C presents a case with increased load – this results in overall generation being slightly higher than in the baseline scenario, while exports are lower and imports are higher. If trade barriers (grid bottlenecks) are removed, the Czech Republic becomes a net importer of electricity for economic reasons (imports mainly from Germany and Slovakia, with continuing exports to Poland and Austria), but continues to export a small amount with no grid reinforcements (Table 12). The reason for this is, again, that grid reinforcements lead to better access to cheaper peaking capacities abroad. Average power prices in this scenario are similar to those in the baseline scenario, but the higher load peaks incur higher peak prices.

Combined with the increased load, the impact of storage is rather low – it mainly shifts PV power to the evening uptake in demand leading to lower exports during the day and lower imports during the evening – leaving the overall balance unaffected. The impact on the distribution grid, where most PV units are connected, may however be significant.

Table 12: Import / export balances.

	Original scenario		Scenario C	
	No reinforce-ments	Optimized re-inforcements	Optimized rein-forcements	No reinforce-ments
Demand	65 TWh	65 TWh	70 TWh	70 TWh
Losses	4 TWh	4 TWh	4 TWh	4 TWh
Net generation	72.99 TWh	71.25 TWh	71.69 TWh	74.65 TWh
Imports	1.42 TWh	2.16 TWh	4.73 TWh	2.58 TWh
Exports	5.40 TWh	4.41 TWh	2.42 TWh	3.23 TWh
Balance	3.99 TWh	2.25 TWh	- 2.31 TWh	0.65 TWh

This is the main result of this scenario – without grid reinforcements, especially gas and hydro power plants show significantly higher capacity factors than in the baseline scenario (Table 13, Figure 28).

Table 13: Annual capacity factors by technology.

Technology	Baseline scenario		Scenario C	
	without rein-forcements	w/ optimized reinforcements	without rein-forcements	w/ optimized reinforcements
Biomass and biogas	60.07%	60.11%	60.10%	60.06%
Natural gas CCGT	37.90%	33.08%	45.53%	35.90%
Natural gas small CHP	92.86%	92.51%	95.63%	94.23%
Natural gas OCGT	21.09%	0.53%	23.97%	0.01%
Hard coal CHP	72.24%	68.48%	79.16%	67.34%
Hydro PS generation	6.28%	1.80%	3.24%	0.53%
Hydro PS pumping	6.50%	2.23%	6.43%	1.35%
Hydro reservoirs	34.50%	10.62%	40.62%	3.66%
Hydro run of river	53.13%	53.08%	53.08%	53.12%
Lignite CHP	72.65%	72.76%	78.70%	76.66%
Nuclear Dukovany	74.99%	74.99%	74.98%	74.99%
Nuclear Temelín	79.46%	79.48%	79.46%	79.47%
PV	11.47%	11.47%	11.36%	11.37%
Waste incineration	99.97%	99.98%	99.98%	99.95%
Wind	26.22%	26.23%	26.25%	26.17%

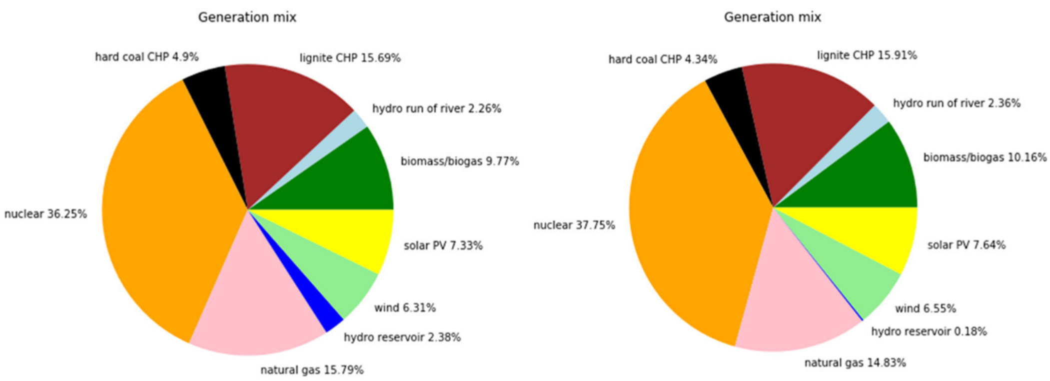

Figure 28: Generation mix by fuel source, Scenario C without (left) and with (right) reinforcements. (Source: Simulation results.)

5.2.2 Reinforcements

The reinforcements determined are given in Table 14. They correspond with the reinforcements from the baseline scenario with one exception: The line to Poland no longer needs to be reinforced as exports to Poland are lower, and transfer flows from Germany and Slovakia also decrease due to higher consumption in the Czech Republic.

Table 14: Grid reinforcements in CZ, Scenario C.

Line	Action	Impact
400 kV Nosovice-Varin (SK)	Two new 400 kV circuits on the lines from Nosovice to Varín (SK)	Corridor Slovakia-CZ-Poland
400 kV line Sokolnice-Prosenice	Additional 400 kV circuit	Corridor Slovakia-CZ-Poland
220 kV line Sokolnice-Prosenice	Upgrade of double circuit line to 400 kV	Corridor Slovakia-CZ-Poland
400 kV line Sokolnice-Stupava (SK)	Two additional 400 kV circuits	Corridor Slovakia-CZ-Poland

5.2.3 Dispatch Examples

The dispatch examples from summer and autumn weeks (Figure 30 to Figure 32) remain relatively the same as the ones in the baseline scenario, albeit with slightly higher gas contribution. Even with the increased load, the Czech Republic exports most of the time. However, the January week in Figure 29 shows that at high winter load, the system really struggles to cover load domestically, Pumped storage can cover the morning peak, but during the evening peak increased by heat pumps and electric vehicles, the system needs to import. This is a similar situation to that of France, which is a great exporter of electricity, but still becomes partially dependent on German imports during winter peak hours.

With this rise in demand, the Czech Republic would need either cold reserve plants for the winter (similar to the case described in more detail in section 2.2.4), or generally a few more power plants if the system is to remain completely self-sufficient. (Weekly generation shares are given in Figure 33.)

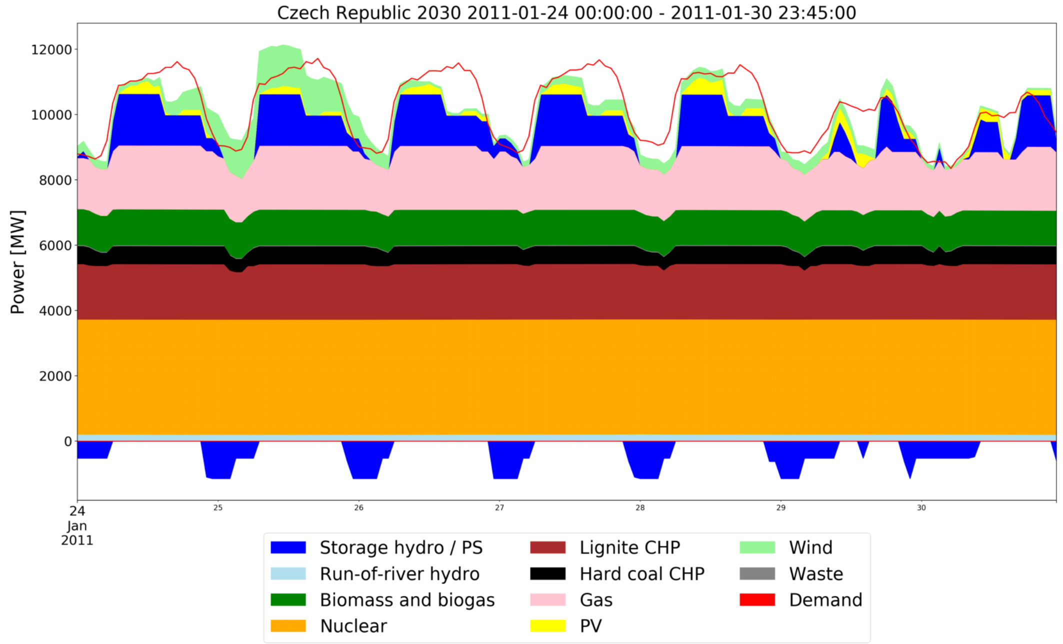

Figure 29: Dispatch in the Czech Republic, Scenario C without grid reinforcements, January week. (Source: Simulation results.)

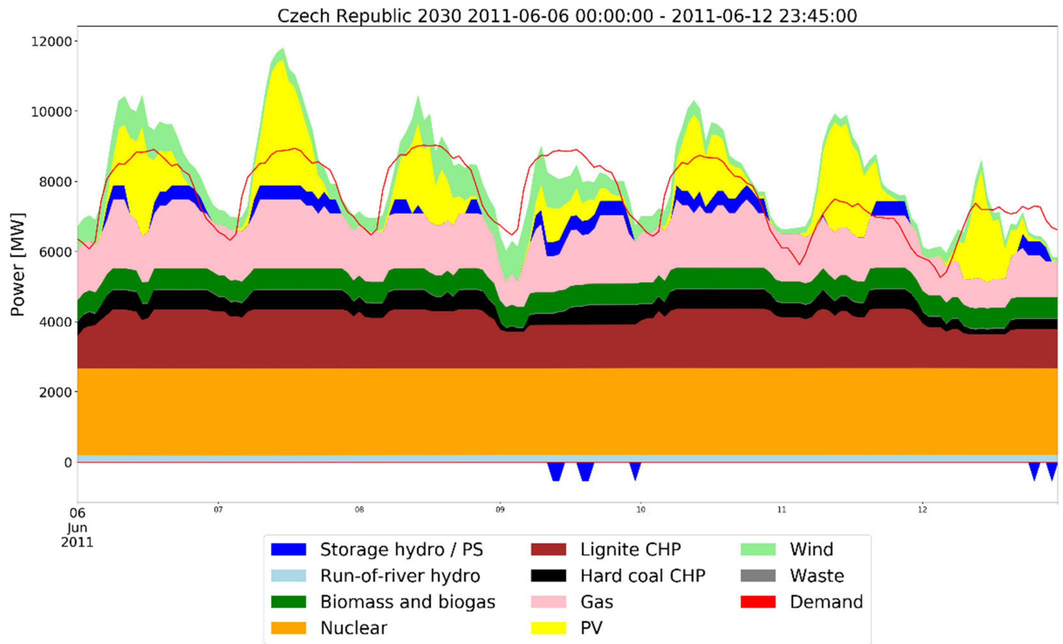

Figure 30: Dispatch in the Czech Republic, Scenario C without grid reinforcements, June week. (Source: Simulation results.)

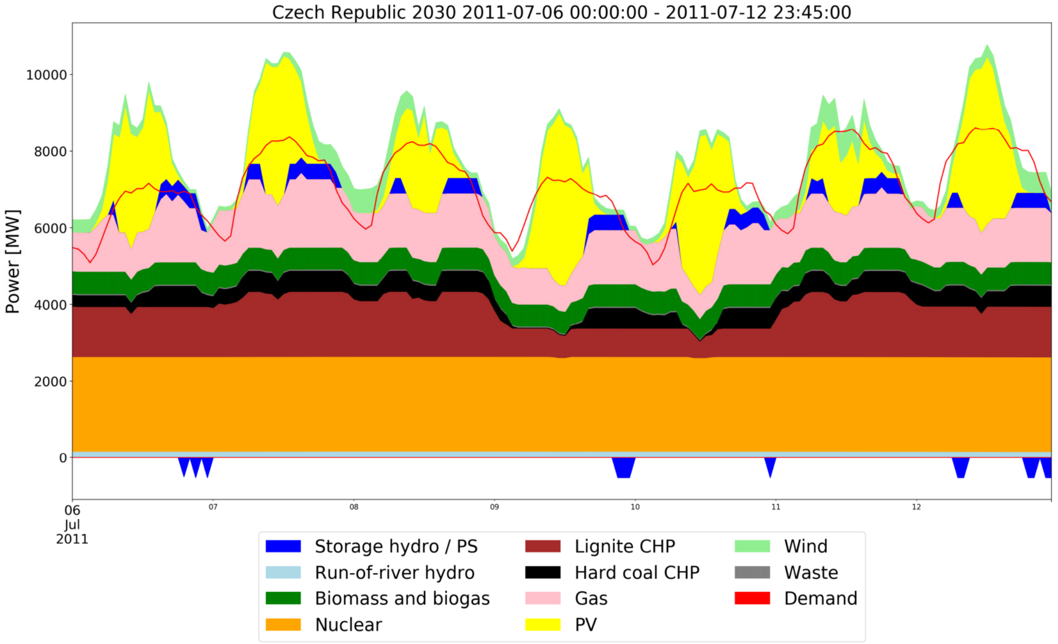

Figure 31: Dispatch in the Czech Republic, Scenario C without grid reinforcements, July week. (Source: Simulation results.)

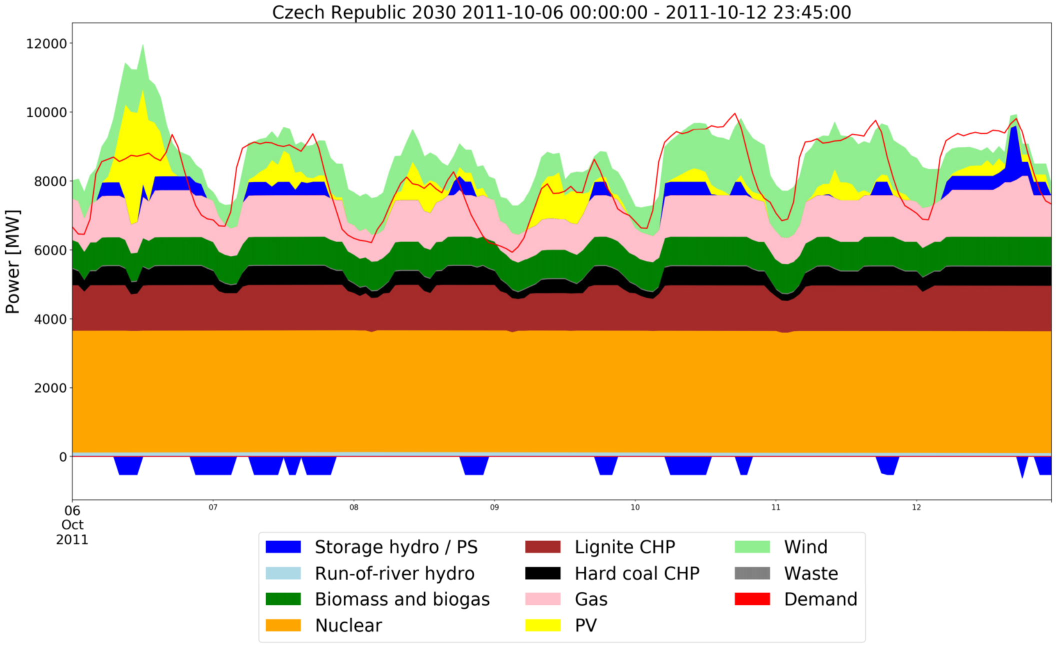

Figure 32: Dispatch in the Czech Republic, Scenario C without grid reinforcements, October week. (Source: Simulation results.)

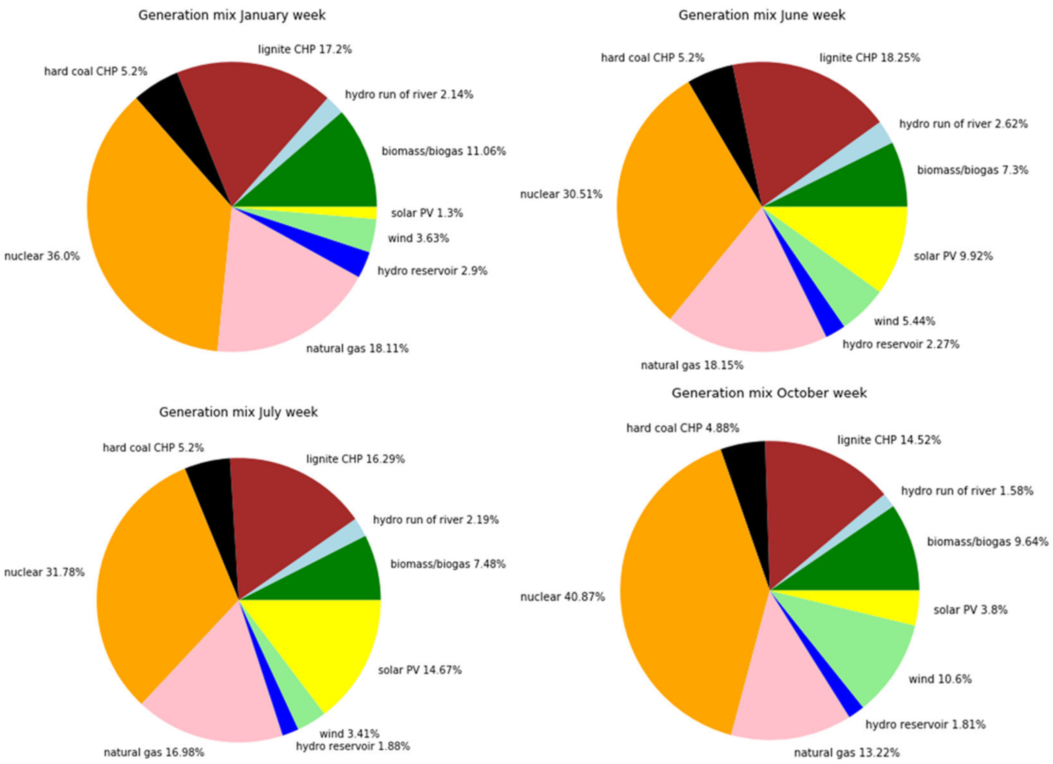

Figure 33: Weekly generation mixes for all four example weeks. (Source: Simulation results.)

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 UPDATED BASELINE SCENARIO

The updated baseline scenario recommendations are in line with those from the original report – the updated hydro model did not change the general outcome. However, the modelling of an additional extremely cold winter week indicates that the Czech system under this scenario is approaching its firm capacity limit. With a further increase in load, a dependence on peak power imports may arise – a result that is confirmed by the Scenario C results, where load is higher.

If the Czech system is to be self-sufficient in the future, the installation of additional renewable energy capacities, backed up by some amount of additional gas fired generation for cold low-VRE periods, is recommended beyond 2030. With increasing VRE shares, the Czech system has a lower demand for baseload capacity (nuclear and lignite), but an increased demand for peak generation that can be provided at a lower cost by gas fired units.

6.2 ADDITIONAL SCENARIOS

A scenario result overview and comparison is given in Table 15. The scenario results are all rather intuitive:

- Replacing a cheap baseload plant (Dukovany) with medium priced CCGT results in less exports and more imports, while firm capacity remains the same;
- Less export capacities in surrounding countries lead to more exports from the Czech Republic, indicating that especially in summer, there are some considerable overcapacities;
- A load increase, especially with demand from electric vehicles and heat pumps stacked on top of the evening peak, brings the system close to its capacity limits.

Table 15: Overview of scenario results.

Scenario	A	B	C
Main difference to baseline scenario	NPP Dukovany decommissioned and replaced with biomass and gas	More opportunities for power export, less for import	Load increased by electric vehicles and heat pumps, additional PV storage
Main impact	Less exports, more imports	More exports, less imports	Less exports, more imports, generation shortage in winter
Identified issues	Slightly more expensive power	High wholesale power prices	Generation shortage in winter
Recommendations	-	Installation of additional capacity to harness income from exports, grid reinforcements	Reserve power plants (flexible peakers would be sufficient, as situations appear frequently, but only for a few hours at a time)

APPENDIX

Table 16: Import and export balances by country.

	O_Curtail-ment	O_Expansion	A_Curtail-ment	A_Expansion	B_Curtail-ment	B_Expansion	C_Curtail-ment	C_Expan-sion
CZ -> Austria								
Exports	6066.42	6744.27	2052.72	4290.83	4666.81	8805.26	6309.78	5324.54
Imports	734.69	1636.50	3833.49	2474.75	1492.05	697.19	668.13	2136.91
Balance	5331.73	5107.77	-1780.77	1816.08	3174.76	8108.07	5641.65	3187.63
CZ -> Germany								
Exports	1358.80	1353.78	3417.94	3693.33	1502.35	1363.75	993.45	1075.99
Imports	8918.34	8754.88	7651.04	7404.39	8762.27	8975.51	9604.26	9222.30
Balance	-7559.54	-7401.10	-4233.09	-3711.05	-7259.92	-7611.76	-8610.82	-8146.31
CZ -> Poland								
Exports	12506.30	15069.80	10566.20	12820.70	11702.57	9345.24	10617.30	14104.29
Imports	51.80	98.71	135.43	126.21	107.77	294.50	119.78	155.36
Balance	12454.49	14971.08	10430.77	12694.49	11594.81	9050.74	10497.53	13948.93
CZ -> Slovakia								
Exports	162.62	484.26	627.44	342.17	1825.09	1301.00	1126.16	485.94
Imports	6403.44	11642.51	4760.17	14276.18	2097.48	6741.61	8001.99	11786.51
Balance	-6240.82	-11158.25	-4132.73	-13934.01	-272.39	-5440.61	-1875.83	-11300.57
All transactions								
Exports	20094.14	23652.10	16664.30	21147.03	19696.82	20815.25	19046.69	20990.76
Imports	16108.27	22132.61	16380.12	24281.53	12459.57	16708.80	18394.16	23301.08
Balance	3985.86	1519.50	284.18	-3134.50	7237.25	4106.44	652.53	-2310.32
Sum Exports	5404.12	4062.67	3238.66	1834.82	7864.61	5578.74	3232.84	2420.18
Sum Imports	1418.26	2543.18	2954.48	4969.32	627.36	1472.30	2580.31	4730.49
Balance	3985.86	1519.50	284.18	-3134.50	7237.25	4106.44	652.53	-2310.32